Review of Goals and Plans for NASA's Space and Earth Sciences

Panel on Review of NASA Science Strategy Roadmaps, National Research Council

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Panel on Review of NASA Science Strategy Roadmaps
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Foreword

The Space Studies Board ascribes considerable significance to this report of the Panel on Review of NASA Science Strategy Roadmaps. During the many years of its existence, the Board has offered NASA advice on the strategies to pursue for a vibrant space and Earth science program. The advice has been delivered through many reports, the most notable of which are the comprehensive decadal science strategies. It is up to NASA, however, to determine how this advice is to be implemented, what is to be pursued in each discipline, and more important, what is the balance to be achieved among the various science disciplines. This report offers advice on the actual implementation of the nation's space and Earth science program.

NASA commissioned various strategic roadmaps for its science disciplines. They are a work in progress and serve as inputs to the NASA planning process. The Board and its review panel, working on behalf of the scientific community, appreciate being able to comment on each and to note their strengths and their weaknesses before NASA acts on them.

The report also offers advice as to the principles that NASA should follow as it integrates the various science discipline plans. This advice is potentially the most significant part of the report because, as would be expected, the sum of the aspirations of the individual NASA roadmaps exceeds what is fiscally possible, and the integration process is where the hard decisions occur.

The Space Studies Board is asked from time to time to review and comment on the content of the NASA space and Earth science program, and we expect that this will occur again. The principles presented here, by which a vibrant space and Earth science program should be assembled, will also serve as the standard against which NASA's activities will be judged.

Lennard A. Fisk, *Chair*
Space Studies Board

Preface

In January 2004 President George W. Bush announced that the U.S. space program would undertake "a renewed period of discovery," and he charged NASA with focusing its efforts on exploration.[a] Subsequently referred to as the vision for space exploration, this policy included human and robotic missions to the Moon, Mars, and beyond. The group appointed by President Bush to recommend how to best implement the new policy—the Commission on Implementation of United States Space Exploration Policy—issued its report in June 2004.[b] The commission endorsed the objectives and actions specified in the president's space exploration vision and recommended that NASA address certain new technology capabilities that the agency would need in its various endeavors during the next several decades. The commission also recommended that NASA "ask the National Academy of Sciences to engage its constituent scientific community in a reevaluation of priorities to exploit opportunities created by the space exploration vision."[c]

Then-NASA Administrator Sean O'Keefe subsequently wrote to the presidents of the National Academy of Sciences and the National Academy of Engineering proposing that the National Research Council (NRC) and NASA consider how to "collectively address the Commission's recommendations."[d] He also announced a new strategic planning process in which NASA would develop a set of strategic roadmaps for each of the major exploration objectives. Finally, Congress in its FY 2005 appropriations bill for NASA directed the "Space Studies Board to conduct a thorough review of the science that NASA is proposing to undertake under the space exploration initiative, and to develop a strategy by which all of NASA science disciplines . . . can make adequate progress toward their established goals as well as providing balanced scientific research in addition to support to the new initiative."[e]

The NRC's initial, partial response to the recommendations of the president's commission and the requests from Administrator O'Keefe and the Congress was provided in the Space Studies Board's February 2005 report *Science in NASA's Vision for Space Exploration*.[f]

Contemporaneously with the preparation of that report and in response to the president's direction, NASA created two complementary roadmapping efforts: a capabilities roadmapping effort and a strategy roadmapping effort. These were to be melded to produce an integrated space exploration

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[a] "President Bush Announces New Vision for Space Exploration Program, Remarks by the President on U.S. Space Policy, NASA Headquarters, Washington, D.C.," January 14, 2004. Available at <www.whitehouse.gov/news/releases/2004/01/20040114-3.html>.

[b] President's Commission on Implementation of United States Space Exploration Policy, *A Journey to Inspire, Innovate, and Discover*, 2004, available at <govinfo.library.unt.edu/moontomars/>.

[c] President's Commission on Implementation of United States Space Exploration Policy, *A Journey to Inspire, Innovate, and Discover*, 2004, p. 9.

[d] Letter dated July 12, 2004, from NASA Administrator Sean O'Keefe to National Academy of Sciences President Bruce Alberts. See Appendix A.

[e] Conference Report (House Report 108-792) to Accompany H.R. 4818 FY 2005 Consolidated Appropriations Bill, Division I—Department of Veterans Affairs, Housing and Urban Development, and Independent Agencies, "National Aeronautics and Space Administration," p. 1.

[f] NRC, *Science in NASA's Vision for Space Exploration*, The National Academies Press, Washington, D.C., 2005.

architecture for the agency. To further assist NASA, and in response to the various requests, the NRC organized separate, independent reviews of the expected NASA roadmaps.

Thirteen committees were charged by NASA to develop strategy roadmaps for each of 13 strategic objectives. These committees included both NASA personnel and outside experts and operated under the Federal Advisory Committee Act, holding public meetings in the spring of 2005. The following 13 strategy roadmaps were planned:

1. Robotic and Human Lunar Exploration,
2. Robotic and Human Exploration of Mars,
3. Solar System Exploration,
4. Search for Earth-like Planets,
5. Exploration Transportation System,
6. International Space Station,
7. Space Shuttle,
8. Universe Exploration,
9. Earth Science and Applications from Space,
10. Sun-Solar System Connection,
11. Aeronautical Technologies,
12. Education, and
13. Nuclear Systems.

When Michael Griffin became NASA's administrator in mid-April 2005, he directed that the agency accelerate the completion of some of the ongoing strategic roadmaps and deferred or redirected other portions of the strategic planning activities. The NRC review efforts were accordingly changed. The Space Studies Board, in collaboration with the Aeronautics and Space Engineering Board, was redirected to conduct two reviews (instead of five), the first to assess NASA's science strategy roadmaps and the second to encompass the results of several ongoing NASA reviews of the future of the International Space Station that had superseded the International Space Station strategy roadmap.

Six science strategy roadmap reports, all of which were produced by committees chartered by NASA's Science Mission Directorate, were provided to the NRC on May 23, 2005, and the NRC's Panel on Review of NASA Science Strategy Roadmaps (see Appendix C for member biographies) met from June 13 to 15 to review them. (The NRC's review of the plans for the space station was deferred to the fall of 2005.) The roadmaps were also provided to members of the Space Studies Board and to its five relevant standing committees[g] to expand the range of perspectives and inputs available to the review panel. The NRC panel also included members of the Space Studies Board and these five standing committees.

The roadmaps reviewed by the panel addressed six objectives: Robotic and Human Exploration of Mars, Solar System Exploration, Universe Exploration, Search for Earth-like Planets, Earth Science and Applications from Space, and Sun-Solar System Connection. The panel did not review NASA's Robotic and Human Lunar Exploration roadmap, which was chartered by the agency's Exploration Systems Mission Directorate but not completed.

The panel was given the following charge:

1. Assess the intrinsic merit of the proposed roadmap objectives and of their proposed implementing programs, especially with respect to relevant NRC or other external advisory reports. Assess whether clear arguments are made for their potential for contributing decisive or transformational technological or scientific advancements.

[g] The standing committees are the Committee on Astronomy and Astrophysics, Committee on Planetary and Lunar Exploration, Committee on Solar and Space Physics, Committee on the Origins and Evolution of Life, and Committee on Earth Studies.

2. Ascertain whether there are any significant gaps or if there are important crosscutting opportunities or scientific infrastructure issues that are not identified and adequately developed.

To the extent feasible, within the constraints of the schedule and the availability of NASA material for review, [the panel will] also consider the following:

- Initial priorities and decision rules for making prioritization decisions;
- Relationships between program elements;
- Schedule, resource, and technology realism; and
- Relationships between NASA and non-NASA participants from the perspective of whether the roadmaps can make adequate progress toward their established goals as well as provide scientific research support of the vision for space exploration.

The panel's review was conducted under an expedited schedule in June and July 2005 so that the results would be available to the government and the public in August 2005.

The panel emphasizes that the roadmaps represent inputs to NASA's strategic planning process rather than final documents representing agency policy. Accordingly, the panel treated the roadmaps as interim inputs to NASA. In response to its charge from NASA and the Congress, the panel evaluated the roadmaps from two perspectives—first, as individual research themes and, second, perhaps more important, as elements of an overarching space and Earth science program of exploration whose integration and prioritization can best be accomplished through application of several fundamental principles.

The panel's findings and recommendations specific to the individual roadmaps are presented in Chapters 2 through 6. Chapter 7 offers recommendations on principles concerning prioritization and integration of the various roadmaps.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their review of this report:

Richard Anthes, University Corporation for Atmospheric Research,
Anthony W. England, University of Michigan,
Larry Esposito, University of Colorado,
Jack Farmer, Arizona State University,
Jacqueline Hewitt, Massachusetts Institute of Technology,
Sara Seager, Carnegie Institution,
Norm Sleep, Stanford University,
David H. Weinberg, Ohio State University, and
Thomas Zurbuchen, University of Michigan.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Alan Dressler, Observatories of the Carnegie Institution. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

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Executive Summary

As charged by NASA and Congress, the Panel on Review of NASA Science Strategy Roadmaps reviewed six science roadmaps. It found that the proposed roadmaps have significant scientific merit and that, with a few notable exceptions, their near-term recommendations are generally consistent with the decadal-scale studies produced by the National Research Council (NRC). The panel believes that the roadmaps are reasonable inputs to NASA's strategic planning/efforts process and together provide rationales for future planning that are generally well supported by the existing NRC decadal surveys.[1-4]

The main sources of gaps and potential missed opportunities in some of the six roadmaps are a shortage of scientific justification for their stated goals and an overly narrow interpretation of the presidential exploration vision by the NASA roadmap teams. If science in pursuit of the exploration vision is to be aligned with the priorities set forth by the scientific community in NRC decadal survey reports, it will be essential for NASA to embrace the broadly based science program that has been recommended by the 2004 report of the President's Commission on Implementation of United States Space Policy[5] and the principles articulated in the 2005 Space Studies Board report *Science in NASA's Vision for Space Exploration.*[6] Also, much more should be done to coordinate planning across the various roadmaps and with other federal agencies. The short timescale for writing the roadmaps and the lack of community input may have contributed to these shortcomings.

The panel was able to draw some broad conclusions from its review, which are provided as general principles for integration and prioritization of the strategic planning to fulfill the exploration vision. These principles are stated briefly in this Executive Summary and in more detail in Chapter 7. The most important result of the roadmapping activity may now be its contribution to a balanced and clearly defined decision process. The panel's key recommendations are that the overall science program be guided by scientific merit and be driven by discoveries.

INDIVIDUAL STRATEGIC ROADMAPS AND RESEARCH THEMES

Robotic and Human Exploration of Mars

The *Robotic and Human Exploration of Mars* strategic roadmap[7] provides a reasonable approach to future Mars science exploration during the next three decades. The roadmap's strengths are its early recognition of broad scientific goals, consideration of preparations for human exploration, and strategies for developing the next generation of Mars scientists. Its major weakness is that the scientific goals are poorly linked to the specific missions, which focus on putting humans on Mars. The roadmap does not present scientific justification for its goal of placing humans on Mars, and the issues of forward and back contamination are not addressed adequately.

The panel recommends careful consideration of the broad science goals and priorities for Mars studies set forth in the NRC decadal survey New Frontiers in the Solar System[8] *when the robotic and human exploration of Mars is being planned.*

To maintain flexibility and ensure responsiveness to new discoveries, the panel recommends that clear budget lines of small- (Scout-class) and medium-scale missions be developed for the long-term robotic exploration of Mars.

Solar System Exploration

The panel finds that overall the proposed missions and timescales in *The Solar System Exploration Strategic Roadmap*[9] have significant scientific merit, and the near-term recommendations are consistent with those of the NRC decadal survey *New Frontiers in the Solar System*. *The Solar System Exploration Strategic Roadmap* appropriately recognizes the importance of timely technology development to support cost-capped missions, and it emphasizes the contributions to NASA's education and outreach program and the need to continue this vital effort.

The panel agrees with the breakdown of goals listed in the roadmap and notes that they are consistent with, and support, the goals outlined in the NRC solar system decadal survey. However, the roadmap uses the concept of planetary habitability as its basic premise for scientific exploration, but it does not clearly articulate how the planned investigations will address planetary habitability and how each proposed mission will build on previous mission results.

The panel recommends that a proper science approach be developed and that clearer relationships between the concept of habitability and missions proposed to demonstrate habitability be articulated and maintained in any future NASA solar system exploration program.

Universe Exploration and the Search for Earth-like Planets

The two roadmaps *Universe Exploration* and *The Search for Earth-like Planets*[10,11] make a strong case for exploring the fundamental physics associated with the beginning of the universe and the nature of space-time and for searching for Earth-like planets. They do not, however, present the most robust case possible for the suite of missions that address the important broad range of astrophysical questions at the forefront of astrophysical research. Not all of these missions fall conveniently in the scope of the Beyond Einstein and the Search for Earth-like Planets programs. The division of topics between these two roadmaps also tends to deemphasize the capability of some of the proposed missions, which are critical to the search for Earth-like planets, to do broader astrophysical research. Finally, the partitioning into two roadmaps has deemphasized the value of shared technology, facilities, and infrastructure.

A significant issue conspicuously absent in the *Universe Exploration* roadmap is the future of the Hubble Space Telescope (HST). In a 2004 report the NRC laid out a continuing science role for HST in astronomy and astrophysics.[12] The fate of HST is intimately connected to the development of other NASA missions in the roadmap.

Much of NASA's former Structure and Evolution of the Universe and Origins programs has been redefined as the Pathways to Life theme, which appears to be an overly narrow interpretation of the vision for space exploration. However, a broader interpretation of NASA's science mission in the exploration vision was described by the president's commission's report *A Journey to Inspire, Innovate, and Discover*[13] and also expressed in the NRC report *Science in NASA's Vision for Space Exploration*.[14] Those reports stated that astronomy can and should be more than the search for life.

The Search for Earth-like Planets roadmap outlines an ambitious plan of large, expensive, and technologically challenging missions; however, the roadmap contains very little discussion of mission costs and technological challenges and milestones that must be met for each mission to be successful. The realism of the proposed mission timeline and the ability of the proposed missions to fit into the budget line are serious concerns.

The panel recommends that broad-based community input be sought to guide decisions about priorities and scientific directions if any significant revision to the Search for Earth-like Planets *strategic roadmap mission sequence becomes necessary.*

Earth Science and Applications from Space

Unlike the other roadmaps, *Exploring Our Planet for the Benefit of Society*, the strategic roadmap for Earth science and applications from space[15] had no NRC decadal survey to guide it. Past NRC studies have articulated the importance of broad community discussion and input as an essential part of NASA's long-term strategic planning—input that will be available after completion of the NRC decadal survey on Earth science and applications that is now in progress.

The panel recommends that the forthcoming NRC Earth science and applications decadal survey be used as a starting point for mid- to long-term planning (i.e., for beyond 2010). Before the completion of the decadal survey, NASA planning and advanced technology programs should remain flexible to avoid commitments to missions that might not receive broad community support. In the near term NASA should focus foremost on the specific recommendations made in the NRC decadal survey interim report.[16] *In particular, attention should be given to the near-term gaps in the current program of long-term observations.*

Interagency cooperation is critical for ensuring long-term operational measurements, and ongoing mission planning will be needed with the National Oceanic and Atmospheric Administration (NOAA), which plays a strong role in atmospheric and oceanic observations. International cooperation also will be important in implementing and enhancing the NASA program.

Recognizing the strong message from the NRC Earth sciences decadal survey interim report that "NASA must retain Earth science as a central priority, to support critical improvements in understanding the planet and developing useful applications,"[17] *the panel recommends that NASA strongly support the Earth science program independent of its involvement in the vision for space exploration*.

Sun-Solar System Connection

The *Sun-Solar System Connection* roadmap[18] is a well thought out document that succeeds in placing many science objectives into the context of the vision for space exploration. The roadmap correctly notes that the science program has reached a level of maturity that allows it to focus on "systems science" that addresses the strong interactions between all of the different components of the Sun-solar system environments, even while essential work continues on the individual constituents. Adjustments have been made to accommodate resources and to support the vision for the space exploration schedule; however, the resulting overall priorities are roughly consistent with the relevant NRC decadal survey[19] and its recent follow-on NRC study.[20] The latter study reexamined the NRC decadal survey recommendations in the context of the objectives of the vision for space exploration.

At the highest level the panel generally supports the science and implementation program developed in the roadmap. However the rationale undervalues the role of fundamental discovery science, instead focusing too single-mindedly on how scientific findings will flow down to other applications and operations interests. This may result in a program that is too narrow to match the broad scientific exploration goals of the vision for space exploration.

PRINCIPLES FOR INTEGRATING SCIENCE STRATEGY ROADMAPS

The panel, in addition to reviewing each of the six roadmaps individually, considered the principles that should be used for prioritization and integration, leading to an overall space and Earth science exploration program spanning more than two decades. These principles are an expansion and amplification of the principles noted in the NRC report *Science in NASA's Vision for Space Exploration*.[21]

Advancing Intellectual Understanding

A guiding principle should be scientific merit, as measured by the advancing intellectual understanding of the cosmos and our place in it. The goals and objectives set in relevant NRC decadal surveys and similar reports should be the primary criteria for setting priorities and program content. These surveys have always striven to identify the most important, revolutionary science that should be undertaken and, as such, have set a high bar of excellence. The NRC decadal surveys have benefited from the broad inputs by the scientific community and are recognized for their credibility and stability. This process has been one of the foundations that has enabled NASA to develop an outstanding scientific program with a long and successful record to its credit. Science that is enabled by exploration should be held to the same standard of scientific merit and advancing intellectual understanding as the science goals embodied and recommended in past NRC decadal surveys.

Program Span, Diversity, Stability, and Flexibility

The integrated science program constructed by NASA based on these roadmaps should have characteristics such that all major scientific disciplines can make progress toward their goals as established in NRC decadal surveys or other similar reports. The program should be discovery driven and not rigid, allowing exciting new discoveries to be rapidly accommodated in a program plan, and should include the broad scientific community's involvement in the decision process. Flexibility is enhanced by having a mix of small, highly responsive missions as well as flagship missions that may take the better part of a decade to complete.

Creating Opportunities for the Future

A robust, sustainable aerospace community is required. Investment in the nation's intellectual and physical infrastructure that provide the basis for the capability for space exploration—and stewardship of that infrastructure—are daunting but essential tasks if we are to continue to be a space-faring nation.

Explicit strategies should be defined for developing the next generation of space scientists and space engineers, and the generation after that. These strategies, which include public outreach and education, need to have a scope commensurate with the scope of the vision for space exploration.

Research and analysis programs, theory programs, and rocket- and balloon-based research programs provide the training and experience base at our universities and research institutes. These programs should be evaluated, judged, and prioritized using the same high standard the panel recommends as applicable to initiatives described in NRC decadal surveys.

Continuing, vigorous development of technology is necessary for the success of the exploration program. Advanced technology needs should be assessed, prioritized, and properly funded so that technologies with long lead times can be developed in time to reduce mission technical risk as well as schedule and cost risk. Multiple-use technologies that are applicable to several branches of the space sciences, for example, those spanning several of the scientific disciplines addressed by the roadmaps, should receive special consideration.

Capabilities to handle the communications and data transmission, storage, and archive needs of the space exploration initiative require assessment and appropriate investment for timely implementation. The NASA roadmap integration and strategic planning process should consider these needs as a vital part of developing the space exploration initiative infrastructure.

Amplifying the Span, Reach, Impact, and Strength of the NASA Exploration Program

The panel's review of NASA strategic roadmaps suggests that NASA research can have societal benefits in addition to increasing fundamental knowledge in science. There is much to be gained by enhancing the connections with other agencies of the executive branch that have responsibilities for or interests in space research and space technology. These agencies include NOAA, the Department of Defense, the Department of Energy, and the National Science Foundation. The impact of space research now transcends the space science community and in many cases involves nonscientists, affecting diverse areas such as agriculture, fisheries, and a host of other enterprises and activities at the commercial, industrial, and state level. An important goal is reinvigorating the transition from space research to operations—typically from NASA to NOAA—and enhancing the ultimate use of the data by a host of enterprises.

International Cooperation and Coordination

NASA has had a decades-long history of international cooperation in human and robotic space activities. Cooperative missions with other nations have provided direct scientific benefits to both the United States and the other cooperating nations. Although the panel recognizes that international cooperation can have its negative aspects as well, the subject should receive serious explicit attention.

The extraordinary scope of the exploration vision and the multigenerational span of this effort provide an opportunity to seek out partners from other nations to join us in this grand adventure. The panel recognizes that current implementation of International Traffic in Arms Regulations (ITAR) continues to be a serious impediment to international cooperation; however, the overwhelming imperative of the exploration vision should provide the basis for a renewed effort to ameliorate the effects of ITAR so that ITAR goals can be obtained without unduly affecting NASA's international cooperation efforts with foreign partners.

CROSSCUTTING OPPORTUNITIES AND ISSUES

The panel was struck by the relative paucity of crosscutting opportunities identified in the six individual roadmaps. To be sure, some opportunities were noted, but it is the judgment of the panel that the scope and span of the opportunities noted in the roadmaps do not do justice to the scope and span of the vision for space exploration

The panel notes two additional crosscutting issues. Although it did not review a lunar roadmap, the panel was concerned about the interrelation between lunar and martian exploration and scientific goals. *Although it recognizes that human lunar exploration goals should be secondary to human Mars exploration goals, the panel emphasizes that lunar science is of great intrinsic scientific interest and should not be neglected under the lunar exploration program.*

The panel also notes that several similar or related missions appear in separate roadmaps. The panel warns that in such cases, desirable but not required missions can seem more important because of multiple appearances in roadmaps. As noted in the prioritization criteria above, *the panel reiterates that every proposed mission should be evaluated on the basis of its scientific merit and ability to meet the goals of the NRC decadal survey in its particular discipline.*

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1
Introduction and Background

NASA's current space and Earth science programs are the result of a strategic planning process that has been refined over many years. Scientific and programmatic priorities, in most cases, are developed by expert committees under the auspices of the National Research Council (NRC), reported on in NRC studies, and translated by NASA into planning documents such as research strategies and then into integrated implementation plans. In their most comprehensive form, these NRC studies have striven to identify the potentially most revolutionary science activities that should be undertaken within a decade.[a] Through this process explicit priorities are set, and numerous missions and concepts are eliminated if the expert committees determine that they do not meet the standard for producing potentially transformational science and intellectual understanding. NASA's current science program exists to transform our understanding of our planet and the cosmos.

As part of its efforts to implement its new exploration goals established in early 2004, NASA has embarked on a strategic planning activity. As noted in the Preface, the strategic planning has recently been accelerated. This acceleration has also affected the NRC review requested by Congress and NASA of the science roadmaps developed under NASA auspices. NASA sought a quick reply in order to integrate the NRC's comments into its current planning and budget process. The roadmaps reviewed by the NRC were as follows:

- Robotic and Human Exploration of Mars,[1]
- Solar System Exploration,[2]
- Search for Earth-like Planets,[3]
- Universe Exploration,[4]
- Earth Science and Applications from Space,[5] and
- Sun-Solar System Connection.[6]

The panel's review of these six roadmaps was informed by the previous NRC decadal studies in the relevant science areas as well as more recent updates to those studies.[b] The fundamental premises of this review were drawn from the guiding principles stated in the February 2005 NRC report *Science in NASA's Vision for Space Exploration*. These guiding principles are as follows:

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[a] The NRC decadal survey process started in the field of astronomy and astrophysics in 1964. The most recent decadal survey in this area produced the report *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001. The first decadal surveys in the fields of solar system exploration and solar and space physics were released in 2002: *New Frontiers in the Solar System: An Integrated Exploration Strategy* and *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, respectively (The National Academies Press, Washington, D.C., 2003). A decadal survey in Earth sciences is currently under way and is scheduled for completion in 2006.

[b] See, for instance, National Research Council, *Solar and Space Physics and Its Role in Space Exploration*, The National Academies Press, Washington, D.C., 2004.

- Exploration is a key step in the search for fundamental and systematic understanding of the universe around us. Exploration done properly is a form of science.
- Both robotic spacecraft and human spaceflight should be used to fulfill scientific roles in NASA's mission to explore. When, where, and how they are used should depend on what best serves to advance intellectual understanding of the cosmos and our place in it and to lay the technical and cultural foundations for a space-faring civilization. Robotic exploration of space has produced and will continue to provide paradigm-altering discoveries; human spaceflight, although fraught with challenges, now presents a clear opportunity to change our sense of our place in the universe.
- The targets for exploration should include the Earth where we live, the objects of the solar system where humans may be able to visit, the broader solar system including the Sun, and the vast universe beyond.
- The targets should be those that have the greatest opportunity to advance our understanding of how the universe works, who we are, where we came from, and what our ultimate destiny is.
- Preparation for long-duration human exploration missions should include research to resolve fundamental engineering and science challenges. More than simply development problems, those challenges are multifaceted and will require fundamental discoveries enabled by crosscutting research that spans traditional discipline boundaries.

In conducting the review, the panel benefited greatly from the guidance of its parent board, the Space Studies Board, as well as from inputs from the standing committees of the Space Studies Board.[c] The panel was briefed in detail on each of the roadmaps by one of the co-chairs of the NASA committees that developed the roadmaps.

Each of the six roadmaps was evaluated using as guidance the charge for this task described in the Preface. Because of the overlapping issues in several roadmaps (such as those involving, for example, the origins of the universe and the search for Earth-like planets, both of which utilize some of the same instruments), some crosscutting issues affecting those roadmaps are noted in the relevant chapters. In Chapter 7, the panel identifies some overarching issues for all of NASA space and Earth science and articulates general principles that the panel believes merit application as NASA proceeds with its strategic planning process to formulate the total exploration program.

In the chapters that follow, the panel has attempted to note where important gaps exist in the science proposed in the roadmaps. The panel is well aware that, collectively, the projects already proposed in the roadmaps likely exceed NASA resources. Nevertheless, the panel discusses areas of science that it believes should compete, along with the areas cited in the roadmaps, for a place in the integrated mission planning. Clearly, the various areas will have to be prioritized in NASA's integrated planning process. In Chapter 7 the panel discusses criteria for establishing priorities.

The panel is also aware that NASA does not currently plan to revise or update the roadmaps reviewed here. Rather, it is expected that NASA will use the roadmaps to inform its development of an integrated research strategy. However, to avoid constant repetition of these points, the panel has structured much of its advice in the following chapters to suggest how the individual roadmaps could be improved. There was considerable variation in the content, structure, and scope of the individual roadmaps, which is reflected in the organization of the advice provided in the report chapters. It is the panel's intent and expectation that NASA will take this advice into consideration as it determines how the roadmaps will be used, either individually or collectively, during the development of a research strategy.

Finally, the panel notes that it recognized that NASA's roadmapping effort, performed simultaneously across multiple fields for integration in an overall strategy, was in many ways a trial run

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[c] The standing committees are the Committee on Astronomy and Astrophysics, the Committee on Planetary and Lunar Exploration, the Committee on Solar and Space Physics, the Committee on the Origins and Evolution of Life, and the Committee on Earth Studies.

for future roadmapping activities, and the panel urges future roadmap committees to better incorporate existing NRC guidance into their plans.

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2
Robotic and Human Exploration of Mars

Given the schedule constraints for generating the roadmaps, the *Robotic and Human Exploration of Mars* roadmap provides a generally reasonable approach to future Mars science exploration during the next three decades.[1] The roadmap's strengths are its early recognition of broad scientific goals, consideration of preparations for human exploration, and strategies for developing the next generation of Mars scientists. Its major weakness is the lack of broader scientific goals and objectives as motivation for the roadmap's specific recommended mission elements, which focus on putting humans on Mars. The roadmap's presentation of the goal of placing humans on Mars appears without scientific justification.

The discussion that follows addresses the major elements of the roadmap from the perspectives of scientific merit, crosscutting opportunities, realism of schedule, resources, technology, prioritization, and decision making, as well as potential relationships with other government agencies for Mars exploration.

SCIENCE GOALS AND OBJECTIVES

The broad goals stated in the *Robotic and Human Exploration of Mars* roadmap's executive summary (most notably in the table) and in the first few pages of the body are consistent with recent NRC documents and overarching themes of Mars science goals.[2-8] However, these early stated goals are disconnected from what is elaborated in the rest of the roadmap. In general, real discussion of prioritized goals, observations, and measurements within the broad science context has been sacrificed to address the human exploration goals. For example, the body of the roadmap repeatedly mentions water and life as science drivers, yet large-scale and important science goals such as characterization of climate (e.g., microclimates and climate history), the radiation environment, polar processes, atmosphere-surface interactions, and the martian crust and interior science are largely ignored. These science goals, equal in importance to the goal of human exploration, are well articulated in recent reports, especially in the NRC report *Assessment of Mars Science and Mission Priorities*.[9] Overall, it is unclear how these science goals feed into the roadmap's planned mission lines.

The panel recommends careful reconsideration of the broad science goals and priorities for Mars studies set forth in the NRC solar system decadal survey New Frontiers in the Solar System *when the robotic and human exploration of Mars is planned using this roadmap. This approach will help reintroduce important science goals into the planning process that are currently underrepresented or missing from the roadmap.*

MISSIONS

The roadmap's retention of existing and previously planned missions (Mars Reconnaissance Orbiter, Phoenix, Mars Science Laboratory, Mars Sample Return) is appropriate and reasonable. These missions are cited and prescribed in numerous past reports and community documents from the NRC and the Mars Exploration Program Analysis Group (MEPAG).[10-12] The inclusion of a possible Mars Environment Mission is also reasonable. However, the panel identified specific problem issues with the roadmap's recommended mission architecture for the coming decade, and the roadmap makes no attempt to identify missions beyond that time. The issues are as follows.

Issues with the 2009, 2011, 2013 Mission Opportunities

Two Mars Science Laboratory (MSL) rover missions are prescribed in the Mars roadmap. However, there is no description of the second MSL (raising questions such as, Would its payload be the same as that of the first MSL?), and there is no justification provided for its scientific need.[a] Furthermore, the NRC's solar system decadal survey recommended that technologies required for sample return be validated during an MSL mission,[13] but that is not part of the mission presented in this roadmap. MSL missions are expected to cost in excess of $1.5 billion, so the decision for a second MSL mission has significant budgetary impacts on the long-range achievability of the overall Mars exploration plan and how long-range science goals are traded off against a second large mission.[14] In addition, it is unclear how the options in the Mars roadmap will be selected, because no decision rules are provided. As presented, NASA's selection of the roadmap's first option would put the Mars Telecommunication Orbiter at risk, threatening future mission communications because current systems are aging.

Similarly, the roadmap presents two possible Mars Environment Mission (MEM) scenarios for 2013—an orbiter or a drilling lander. Again, the MEM descriptions focus solely on the precursor-to-human-exploration aspects of the missions and, as such, represent a diversion from previously recommended missions (Mars Long-Lived Lander Network and Mars Upper Atmosphere Orbiter) for the next decade.[15] Although a decision on which MEM option to pursue is recommended for 2008, no science-based decision rules are given. Nor is there a technology development timeline that would lead to a decision point based on the technological readiness of autonomous drilling should the drilling lander option be selected.

Issues with the 2016 Mars Sample Return Opportunity

The Mars Sample Return (MSR) mission is arguably the cornerstone of Mars exploration science as articulated in previous documents and in this roadmap.[16-19] However, sample return comes with a plethora of critical forward and back contamination issues concerning sample collection, handling, and quarantine that are not addressed in this roadmap. Significant technological hurdles associated with return and described elsewhere[20-24] are also not considered. The NRC has previously estimated that at least 7 years will be required to prepare a quarantine facility, which will strain the schedule of a launch only 9 years away.[25] The quarantine facility, other infrastructure, and enabling technologies (e.g., containment, sterilization, or both) need to be considered as carefully as the human exploration architecture.

SCIENTIFIC UTILITY OF HUMANS ON MARS

Identification of the scientific need for and value of humans in future Mars exploration is conspicuously absent from the Mars roadmap. A case can be made for the science value of humans in

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[a] In briefing the panel, the representative of the NASA roadmap committee noted that two MSL spacecraft were recommended to mitigate the technical risk associated with executing a complex, high-priority mission that would depend on new entry, descent, and landing systems in the particularly challenging environment of Mars. In this report the panel's assessment of having two MSL missions focuses on the scientific balance implications for the overall program and the capacity of the program to maximize scientific return.

space exploration (e.g., their ability to perform complex experiments beyond the capabilities of robots, such as deep subsurface drilling), and program content should reflect this benefit. Moreover, the roadmap should recognize and address the non-science motivation for a human presence. Although it is clear that a major motivation for proposing human exploration of Mars involves national prestige and inspiration for the entire world, the charge for this panel compels it to address the scientific elements of such an effort.

An underlying assumption in the roadmap is that the surface of Mars either is habitable or can be made habitable for future human exploration. However, unlike the lunar surface, soils of Mars may be hazardous (highly acidic, potentially corrosive, toxic), and there is a real potential that human exploration may be prohibited, restricted, or delayed for safety reasons.[26,27] In addition, current international restrictions are in place concerning both forward and back contamination of other habitable planets and the return of materials from Mars.[28,29] A primary goal of the Mars Exploration Program is to understand the potential for life and to explore habitats for possible signatures of extinct or extant life. Discovery of past or present indicators of life would clearly have a transformative impact on many fields of science. However, placing what is essentially an Earth biosphere on Mars can compromise these goals, and there may be quarantine restrictions on materials astronauts have used that have come in contact with the martian surface. Because the roadmap emphasizes a human presence over other scientific endeavors, it opens the risk that the Mars science program could be jeopardized should the human exploration of the planet prove to be hazardous or impossible because of restrictions on cross-contamination with Earth.

The panel's evaluation concerns are heightened in this case, because the considerable expense of human expeditions to Mars may have an adverse effect on the funding available for robotic science.

MISSION CLASS SIZE AND MIX

The Mars roadmap does not characterize mission lines by size (small, medium, large), making it difficult to consider the reasonableness of required resources in relation to budgetary constraints. However, estimates from other sources indicate that MSL and MSR missions will be in the large flagship class (i.e., in excess of $1 billion) and will put pressure on Mars program resources.[30,31] A second MSL rover mission could push MSR out into the 2020 decade. The smaller Scout missions represent community-driven science that is consistent with previous objectives. The NRC solar system decadal survey strongly recommended that Scout missions receive the same commitment as sample return. However, the Mars roadmap's recommended missions put Scout missions at risk, especially if a second MSL is chosen. Furthermore, although the roadmap acknowledges that specific Scouts cannot be defined now for the future, the fact that much high-priority science will not be accommodated in the main mission lines should allow identification of several high-priority Scout mission scenarios or science areas. In general, the lower-cost, high-science-return Scout mission line is underrepresented in the roadmap. Furthermore, after Mars Telecommunication Orbiter (MTO) no plans are presented for a medium-class mission line—instead it appears that resources will be directed into a larger flagship budgetary class.

The panel believes that the lack of smaller missions puts science discovery at risk, and it recommends that clear budget lines for small- (Scout-class) and medium-scale missions be developed for the long-term robotic exploration of Mars.

CROSSCUTTING OPPORTUNITIES

Because resources are limited, NASA should identify areas in which missions can serve multiple scientific goals. There are many crosscutting opportunities between the roadmaps. Several important crosscutting opportunities for the *Robotic and Human Exploration of Mars* roadmap follow:

- *With Sun-Solar System Connection.* There is potential for a shared or partnership approach to achieve multiple scientific goals. Although the interplanetary radiation environment is fairly well characterized, the very intense solar energetic particle events that may require action remain poorly understood and very difficult to predict. The *Sun-Solar System Connection* roadmap recommends a Mars radiation environment and space weather mission, as well as an Inner Heliospheric Sentinels mission to study hazardous solar energetic particle events.

- *With Lunar Exploration.* The panel commends the Mars roadmap's recognition that requirements for human exploration at Mars should drive human lunar exploration. To maintain this important perspective, it is necessary that there be close collaboration and communication between the two programs to ensure unity between them.

The panel recommends that NASA formally link all robotic and human lunar exploration to the robotic and human Mars exploration program's needs and requirements. The scope of this linkage should include science, technology, and infrastructure.

- *With Earth Science.* The Mars roadmap mentions the problem of working with large data sets and an ever-increasing volume of data. Work in the Earth science community with large global data sets integrated across instruments on multiple platforms can serve as models for this task. Utilization of previous Earth science experience and collaboration on future developments in this area would benefit both programs.

OTHER ISSUES

Infrastructure

The Mars roadmap identifies key workforce needs and facilities required to support the Mars Exploration Program. However, two equally important core infrastructural needs for the next decade of exploration recommended in the roadmap are autonomous drilling (a MEM option) and a sample quarantine facility and related infrastructure (for MSR). The infrastructural issues for meeting the mission timelines during the next decade are significant and are underemphasized in discussion in the roadmap. The NRC has produced recommendations for MSR infrastructure in previous studies.[32,33]

Priorities and Decision Rules

Although the Mars roadmap lays out a strategy to "define, downselect, and confirm" a human exploration architecture,[34] it does not describe a similar process for selecting various mission option paths, the population of those missions with scientific goals and objectives, or architectures for nearer-term objectives such as preparation for and implementation of MSR. The roadmap is also not clear about how the mission sequence depends on new discoveries. For example, does MSR depend on any specific discoveries (e.g., organic carbon) in precursor missions?

Schedule, Resource, and Technology Realism

As indicated above, the budget and schedule for two MSLs appear overambitious. Cost estimates suggest that a single MSL will be in the large, flagship mission class (greater than $1 billion).[35,36] A second MSL poses significant fiscal and schedule risk and will likely push the whole Mars program out by at least one mission opportunity and will put accomplishing other goals in the program at risk. In the single-MSL option, a critical technical risk is posed in that a Mars Telecommunication Orbiter may not be present for communications to MSL. In general, the phasing of resources in regard to logistic, operational, and technical needs is not sufficiently considered for the phase-1 portion of the Mars roadmap. For example, the significant technological and infrastructure needs for MSR are inadequately addressed.

NASA and Non-NASA Participants

There is no substantial discussion in the Mars roadmap concerning participation of other NASA and non-NASA entities in the program. The panel encourages the broad integration of required observations across traditional discipline lines within NASA and in concert with other U.S. agencies and international partners. Specifically, within NASA, a number of complementary goals are recognized that are relevant to understanding the environment on and around Mars within which human exploration will take place. Some of these are addressed in the other roadmaps and in the NRC report *The Astrophysical Context of Life*.[37] Beyond NASA, there is a potential for contributions in this area from the National Science Foundation, the National Institutes of Health, the Department of Energy, and the U.S. Department of Agriculture, as outlined in the NRC report *Life in the Universe*.[38] These other federal agencies can provide input with regard to assessment of the radiation and biological hazards posed by the martian environment and definition of life-detection methods to be utilized in situ.[39,40]

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3
Solar System Exploration

The panel finds that overall the proposed missions and timescales in *The Solar System Exploration Strategic Roadmap*[1] have significant scientific merit, and the near-term recommendations are consistent with those of the NRC solar system decadal survey *New Frontiers in the Solar System: An Integrated Exploration Strategy*.[2] The solar system roadmap appropriately recognizes the importance of timely technology development to support cost-capped missions and emphasizes the contributions to NASA's education and outreach program and the need to continue this vital effort.

SCIENCE GOALS AND OBJECTIVES

One major area of concern this panel has with the solar system roadmap is that the concept of "habitability" is central to the roadmap but is not well developed in regard to scientific lines of enquiry and appropriate missions to respond to those scientific questions. A second, overarching concern is that habitability is the basic premise for scientific exploration in this roadmap. Although habitability is clearly of great importance, the panel thinks that it is inadequate as the sole theme for solar system exploration and thus it undermines the role of fundamental discovery science.

The roadmap addresses the issue of habitability across two broad themes: (1) habitability in planetary environments and (2) habitability associated with planetary system architecture. Within that context five objectives are identified: (1) learn how the Sun's family of planets and minor bodies originated, (2) determine how the solar system evolved to its current diverse state including the origin and evolution of Earth's biosphere, (3) explore the space environment to discover potential hazards and search for resources that would enable permanent human presence, (4) understand the processes that determine the fate of the solar system and life within it, and (5) determine whether there is or ever has been life elsewhere in the solar system. The fundamental issue of how planetary systems become habitable is addressed in this roadmap from two complementary perspectives—comparative exploration of worlds and exploration of planetary architecture. Both threads connect this roadmap to other strategic roadmaps through the exploration of Mars as a once habitable world, the exploration of the Moon as a preserved record of the earliest evolution of Earth and its impact environment, and the potential variety and habitability of planetary systems around other stars.

The panel agrees with this breakdown of goals and notes that it is consistent with, and supports, the goals outlined in the NRC solar system decadal survey. However, the panel cautions that the question of whether the basic requirements for the origin and persistence of life were present at some time during the history of a planet is complex. It is generally accepted that the requirements for life are reduced to three basic components: (1) liquid water, (2) sources of basic building blocks (carbon, hydrogen, nitrogen, oxygen, phosphorus, plus minor elements), and (3) sources of energy. Initial steps to evaluating the habitability of a planetary environment require a determination of whether or not this combination of requirements was present long enough to allow life to originate, evolve, and persist. The roadmap uses the concept of habitability as its basic premise for scientific exploration, yet in its current form it does not clearly articulate how the planned investigations will address these requirements for life and how each mission will build on previous mission results. In addition, nowhere is objective 3, which is concerned with the search for potential hazards and resources, addressed with respect to habitability or in any other context.

The panel recommends that where habitability is determined to be the main focus for exploration, a proper hierarchy of scientific goals and objectives be developed and stronger pathways between the concept of habitability and proposed missions be articulated and maintained. The panel also recommends that basic discovery science should not be ignored in any future promulgation of the solar system roadmap science and implementation program.

MISSION CLASS SIZE AND MIX

In contrast to the NRC solar system decadal survey, which spanned from 2003 to 2013, this roadmap extends from 2005 to 2035. Phase 1 of this roadmap adheres to the criteria that were established in the NRC solar system decadal survey. Missions that were deferred in that report required technology development that would not be available in that decade. This roadmap is clearly influenced by the current success of the Cassini-Huygens mission, and the roadmap includes a flagship mission to Titan. The panel supports the roadmap phase 1 plan. However, for phases 2 and 3 the plan suffers from incomplete articulation and unclear science flowdown.

Each theme addressed in the solar system roadmap addresses previous decadal survey and NASA roadmap goals through a mix of missions of different classes: small Discovery-class missions ($300 million to $500 million), medium-class New Frontiers missions ($500 million to $800 million), and flagship-class missions ($800 million to $1,400 million or $1,400 million to $2,800 million). The panel endorses this breakdown, which follows the lines of the NRC solar system decadal survey in classifying different missions into classes dependent on budget and timescale objectives. Such a classification enables this roadmap to be directly compared with the NRC decadal survey document for ease of use and implementation by the planetary science community, which is becoming accustomed to thinking about space exploration within these discrete class boundaries.

The roadmap appropriately recognizes the importance of the medium-class New Frontiers missions as a vital resource for the planetary community, not only because they have the potential to return unprecedented scientific data, but also because they sustain capabilities and train new generations of planetary scientists. The roadmap describes New Frontiers-class mission priorities as they are addressed in the NRC solar system decadal survey, and the highest-priority missions from that report are reiterated in the roadmap (Venus In Situ Explorer, Comet Surface Sample Return, Jupiter Orbiter with Probes, Lunar Aitken Basin Sample Return). The roadmap recognizes that the current program is based on implementing those missions.

The recent selection of the Juno polar orbiting Jupiter spacecraft (announced after the roadmaps were completed) has altered the context of the roadmap, resulting in the definition of a new track since the construction of the roadmap. However, the competitive nature of the New Frontiers mission line forestalls the planning of a specific mission queue; as indicated in this roadmap, the initial list recommended by the decadal survey should be expanded using community-wide input. The decadal constraint of the decadal survey report is reflected in phases 2 and 3 of the roadmaps.

The panel recommends that roadmap activity be continued in order to optimize science flowdown as new scientific results and technology become available.

As with the New Frontiers program, no recommendations are made in the roadmap with respect to the scope of science that is to be done in the context of the Discovery program. Although openly competed, this program is discussed in the roadmap only as a vehicle for studying small bodies. However, the recent increase in the cost-cap and launch vehicle capabilities (see, e.g., *NASA Research Opportunities in Space and Earth Sciences—2005*[3]) may enable missions to be proposed that were previously outside the Discovery scope, as well as those outside the scope of the roadmap.

The panel recommends that the Discovery program be considered an integral part of any future plans for solar system exploration.

The five flagship missions chosen by the roadmap committee have the potential to produce science that is paradigm altering. The targets of flagship missions include the surface of Venus, the lower atmosphere and surface of Titan, the surface and subsurface of Europa, the deep atmosphere of Neptune and the surface of its moon Triton, and cryogenically preserved samples on the surface of a comet nucleus. The roadmap appropriately recognizes that basic technology is required to implement both mid-sized and flagship missions; however, the panel strongly believes that the roadmap seriously underestimates the size of some of the missions. A Neptune mission that includes a Triton lander and deep probes into Neptune is a major mission. It is not convincing that either a Titan Explorer with a retractable surface probe or a Venus Explorer with an extended stay on the surface could possibly be a "small" flagship. Related to this point is the fact that the solar system roadmap suffers from a lack of discussion or clarity about how technology paths for outer solar system exploration will be achieved. These missions have significant lead times, and technology requirements must be clearly laid out if they are to succeed. Some of the required technology development may also overlap with that required by other roadmaps.

The panel recommends that any future solar system roadmaps include realistic cost analyses to a level of detail consistent with the class of mission. In addition, the panel recommends that technology paths and decision points be clearly specified.

CROSSCUTTING OPPORTUNITIES

This roadmap does not address overlaps with the *Robotic and Human Exploration of Mars* roadmap or the *Sun-Solar System Connection* roadmap. Missions to the Moon, Mars, or solar environment that are designed to support the vision for space exploration will return science data, and these data will likely be highly significant for understanding of the origin and evolution of the solar system and therefore for the goals of this roadmap. A shortcoming of the roadmap is that it does not provide a summary of the extent to which the selected missions in this roadmap will fulfill the five primary science objectives, nor does it integrate contributions from the other roadmaps. *The panel recommends that scientific and technical goals common among this roadmap and other roadmaps be highlighted and linked in future planning efforts.*

The panel endorses the roadmap's recommendation of a Europa Geophysical Orbiter mission, which is also strongly supported by the NRC solar system decadal survey. A Venus flagship mission is promoted in the roadmap in the context of habitability; however, the roadmap fails to address the need for improved understanding of Venus to support comparative terrestrial planetology. The panel notes that Venus mission planning would have benefited by linking with the *Sun-Solar System Connection* roadmap that recognizes Venus relative to global warming on Earth. *The panel recommends articulation of such crosscutting themes in future planning efforts and Venus mission development.*

CAPABILITY ISSUES

Conspicuous by its absence in the roadmap is a significant discussion of the necessity for upgrading NASA's Deep Space Network (DSN), developing enhanced telecommunications capabilities, or providing facilities to handle the data. With the increased number of missions active at any one time (including the ever-rising number of extended missions) and the DSN already pushing the limits of its capability, the need for enhanced telecommunications is becoming ever more urgent. The roadmap devotes a short paragraph to the need for DSN upgrades and acknowledges that the Mars program is leading that development. It does not describe the scope of expected data rates or address issues related to data access, processing, and archiving. The requirements of solar system exploration in this regard are of the utmost importance and must be addressed. *The panel recommends that any future solar system* *exploration planning consider the necessity of adequate support for mission telemetry and that new telecommunications technologies be considered for development.*

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4
Universe Exploration and the Search for Earth-like Planets

The *Universe Exploration* roadmap and *The Search for Earth-like Planets* roadmap represent the two major research components of the Universe Division at NASA headquarters.[1,2] These research components are supported by the most recent NRC astronomy decadal survey in this area and related reports.[3-5]

These two roadmaps make a strong case for exploring the fundamental physics associated with the beginning of the universe and the nature of space-time and for searching for Earth-like planets. They do not, however, present the most robust case possible for the suite of missions that address the important broad range of astrophysical questions that are at the forefront of astrophysical research but do not fall conveniently in the scope of the Beyond Einstein and the Search for Earth-like Planets programs as presented in these roadmaps (see the next two sections). It is imperative that a proper balance be struck along the complete spectrum of astrophysical research. The division of topics between these two roadmaps also tends to deemphasize the capability that some of the proposed missions critical to the search for Earth-like planets have to do broader astrophysical research. Finally, the partitioning into two roadmaps has deemphasized the value of shared technology, facilities, and infrastructure.

UNIVERSE EXPLORATION ROADMAP: FROM THE BIG BANG TO LIFE

The Beyond Einstein mission suite addresses exciting and fundamental physics questions designed to test whether or not there are observable limits to Einstein's theory of gravity. A strong case is made for exploring the beginnings and evolution of the universe—one of the 5 fundamental questions identified in the NRC's *Astronomy and Astrophysics in the New Millennium*[6] (the AAp decadal survey) and one of the 11 identified in *Connecting Quarks with the Cosmos*.[7] A strong emphasis on studying the details of black hole and space-time structure as well as dark energy reflects the endorsement of these activities in the NRC's AAp decadal survey, *Connecting Quarks*, and *Physics of the Universe*[8] reports. The roadmap's emphasis on the Laser Interferometer Space Antenna (LISA) and Con-X missions is in line with priorities of the AAp survey as well as a recent NRC letter report.[9]

The roadmap discusses science-driven (not budget-driven) branch points and decision rules. The science criteria are designed to provide flexibility in defining, prioritizing, and designing future missions. There is clearly a need to maintain options to be addressed in future budget and scientific contexts.

In the Beyond Einstein program, there is provision for only one Beyond Einstein Probe mission before the middle of the 2020 decade. At present, missions of the scale of the Dark Energy Probe and the Inflation Probe cannot be funded. Such missions are needed to accomplish some of the specific high-priority science objectives (such as the Joint Dark Energy Mission in the *Universe Exploration* roadmap) and to enable a flexible response to new scientific opportunities.

The elements of NASA's former Structure and Evolution of the Universe and Origins programs that have not been put into the *Search for Earth-like Planets* roadmap have been awkwardly incorporated into the Pathways to Life (PTL) theme in the *Universe Exploration* roadmap, so that they are represented by only one of the four primary roadmap objectives. The majority of forefront astronomy and astrophysics research endorsed by the AAp decadal survey is meant to be represented under this umbrella theme of PTL, a move apparently motivated by an unnecessarily narrow interpretation of the vision for space exploration. A much broader vision of NASA's science mission in the exploration vision is described by the president's commission's report *A Journey to Inspire, Innovate, and Discover*[10] and the NRC report *Science in NASA's Vision for Space Exploration*.[11] A February 2005 NRC letter report explicitly echoes the president's commission that "maintaining the breadth of the astronomy and astrophysics enterprise at NASA is consistent with the new exploration vision."[12] The designation "Pathways to Life" has no previous heritage in NASA or NRC documents. *The panel recommends that the nomenclature "Pathways to Life" be abandoned and that NASA develop coherent new themes in the Universe Division that will do justice to the Beyond Einstein program, the Search for Earth-like Planets program, and all the other science highlighted in the AAp decadal survey that the roadmap has agglomerated into Pathways to Life, but that represents vibrant science deserving of separate emphasis.*

The current roadmap does not enunciate well all the transformative science objectives within the PTL theme and hence may not adequately follow NRC recommendations. For example, among the five fundamental questions outlined by the AAp decadal survey are, How do galaxies first arise and mature?, How are stars born and how do they live and die?, and How do planets form and change as they age? The *Connecting Quarks* report also lists understanding how the heavy elements were made as one of the key science questions for the new century. Dark matter is mentioned only briefly in the roadmap and gamma-ray bursts not at all, whereas these topics are significant elements of the AAp decadal survey and *Connecting Quarks* reports. Whether and how these areas of astrophysics are to be addressed in the NASA mission plan outlined in this roadmap are not made clear. This roadmap does not give a comprehensive PTL strategy with a well-sequenced PTL mission progression. Some areas of astrophysics (e.g., those with more tenuous connections to PTL) may thus be vulnerable to exclusion from planning in the Universe Division. *The panel recommends that while maintaining appropriate objectives such as Beyond Einstein, the Search for Earth-like Planets, and other topics as distinct entities, NASA should always consider them in combination for purposes of strategic planning, technology development, and budgeting. This approach would allow a more effective statement of the science justification for the broadly capable missions and a more accurate assessment of technology needs and the costs of achieving Universe Division science objectives.*

The *Universe Exploration* roadmap was clearly constructed with a rigorously self-imposed, narrowly focused approach, with the intention of protecting a core suite of missions within a presumed flat budget. This approach led to omission of important science objectives as outlined above and restricted discussion of missions. The panel is concerned that the circumstances under which this roadmap and the *Search for Earth-like Planets* roadmap were produced (pressure to align the roadmaps to a narrow view of the objectives of the vision for space exploration, changes in direction to the roadmap teams during the task, time pressure, and absence of peer review) led to some emphasis on missions that were known to NASA roadmap committee participants but that did not necessarily reflect the consensus of the AAp decadal survey. This relatively narrow focus also led to some pressure to name and describe some notional missions (e.g., the Inflation Probes) but not others in an attempt to get "in the queue." Planning on single-decade timescales has been productive scientifically, but on longer timescales it is quite difficult to plan without knowing what will have been learned and what technologies will have become available. Therefore suggestions by the roadmap committee for missions in the far term cannot be interpreted as current community endorsement of particular missions.

The laudable strategy of preserving and supporting the Beyond Einstein mission line nevertheless marginalizes the PTL theme. All missions discussed in the roadmap in the PTL timeline are already in progress, apart from a notional "Pathways to Life Observatories" that appears two decades in the future. Beyond missions in the next decade, the roadmap balance between these two types of missions is not consistent with previous NRC recommendations. The scientific cases for the James Webb Space Telescope (JWST) and the Stratospheric Observatory for Infrared Astronomy (SOFIA) are only weakly connected to the PTL theme in the roadmap and are much more strongly articulated in the AAp survey.[13]

That the roadmap committee was “circumspect about mentioning missions whose primary residence is in another roadmap”[a] is a direct result of the desire to support the Beyond Einstein program, but it threatens support for NASA missions (e.g., Space Interferometry Mission (SIM), Terrestrial Planet Finder-Coronagraph (TPF-C), Terrestrial Planet Finder-Interferometer (TPF-I)) that share technology challenges with this roadmap (see “Crosscutting Capability Issues,” below) and potentially support PTL themes through their broader astrophysical components beyond exo-planets.[b] The strong linkage of this roadmap to the *Search for Earth-like Planets* roadmap is mentioned, but it is not implemented in any practical way in the mission timeline. As stressed in an NRC letter report,[14] general astrophysics applications of exo-planet missions are critical to enabling transformational science in a range of disciplines. The NRC has previously noted that the new focus on an accelerated and an exclusively exo-planet-driven design for TPF-C also has adverse effects on other Universe Division goals, including Beyond Einstein.[15,16] These various problems result from “stove-piping” as reflected in both the *Universe Exploration* and the *Search for Earth-like Planets* roadmaps and are at least partly attributable to the current partitioning of the Universe Division program. *The panel recommends that NASA support the exciting fundamental research outlined in this roadmap for the Beyond Einstein program, but also give due consideration to the transformative science objectives outlined by the AAp decadal survey and encompassed in the broad origins, evolution, and fate themes articulated by the President’s Commission on Implementation of United States Space Exploration Policy, which are not well enunciated in the Pathways to Life theme*.

A significant issue that this roadmap does not address is the future of the Hubble Space Telescope. In a recent report the NRC laid out a continuing science role for Hubble that includes both Beyond Einstein and PTL questions.[17] The fate of Hubble is intimately connected to the fate of other NASA missions. *The panel recommends that NASA’s planning take into account the high priority accorded to the Hubble Space Telescope in past NRC decadal survey reports and the recent NRC report* Assessment of Options for Extending the Life of the Hubble Space Telescope.[18]

The AAp decadal survey report encouraged cooperation among agencies. Opportunities for relationships with non-NASA participants are already in place for some missions in the timeline (e.g., with the Department of Energy for the Gamma-ray Large Area Space Telescope (GLAST) and the Joint Dark Energy Mission (JDEM)), and others not mentioned in the roadmap are also possible.[19] The AAp survey report also encourages international collaboration, and it cites a joint NRC-European Science Foundation report, *U.S.-European Collaboration in Space Science*, which addresses many practical aspects of collaboration.[20] GLAST, LISA, and JWST are explicitly mentioned in this context, as well as the TPF connection to the Darwin mission in Europe.

SEARCH FOR EARTH-LIKE PLANETS ROADMAP

The Search for Earth-like Planets roadmap presents two science objectives of strong merit: (1) the search for and direct detection and characterization of Earth-like extrasolar planets and (2) the study of the formation and evolution of extrasolar planetary systems from stellar disks. The discovery of truly Earth-like planets around nearby stars would be transformational; the discovery of spectroscopic signatures of possible Earth-like life on planets around other stars would be revolutionary. Objective 2 is required to give the deepest understanding of the context of objective 1.

The rationale for the mission suite of Kepler, SIM, TPF-C, and TPF-I and the notional Life Finder mission is well laid out and corresponds to the exo-planet investigation priorities defined in the AAp survey report. However, the important broad astrophysical applications of these missions, as outlined in that report, are not addressed in either this roadmap or the *Universe Exploration* roadmap. The

[a] Kathy Flanagan, reply to “Questions for Roadmap Briefers: Universe Division,” June 14, 2005.
[b] Kathy Flanagan, “Universe Exploration: From the Big Bang to Life,” presentation at Review of NASA Strategic Roadmaps: Science Panel, Washington, D.C., June 13, 2005.

roadmap's discussion and justification of missions related to the overall problem of star and planet formation, such as the current Spitzer Telescope and Hubble Space Telescope and the future JWST, SOFIA, and the Single Aperture Far-Infrared (SAFIR) mission, are much sparser and less well connected to community priorities than were the discussion and justification presented in the AAp decadal survey report. The panel notes that JWST was the top priority in the AAp decadal survey report for all ground- and space-based astronomy.[21]

The proposed mission line consists of a Discovery-class mission (Kepler) followed by a series of large, complicated, and expensive missions (SIM, TPF-C, TPF-I). The roadmap attempts to discuss the interdependencies of these missions and to introduce important decision points, but the only real options presented are (1) to cancel TPF-C and proceed directly with SIM and accelerate TPF-I if Kepler shows that $\eta_\oplus$ (the frequency of habitable Earth-like planets around solar-type stars) is 0.01 or less and (2) "to solicit proposals for rapid development low-cost missions" if a very nearby terrestrial planet should be discovered. With a Kepler launch in 2008 and a determination of $\eta_\oplus$ coming 4 years later in 2012, the first decision point will be moot, given the current schedule of the start of TPF-C phase A in 2006 and the goal of a launch in 2014. Similarly, the first scientific results from SIM will be too late to influence the design of TPF-C. The need for science precursor missions to drive the design of both TPF-C and TPF-I and the importance of the astrophysics goals of TPF as stated in the AAp decadal survey report were discussed in a recent NRC letter report.[22] The roadmap shows little, if any, acknowledgment of these concerns. For example, the descoping of SIM that is currently under consideration by NASA would have strong negative effects on the value of TPF for areas of astrophysics beyond the mission's goals for planet searching. *The panel urges NASA to ensure that appropriate TPF precursor science is done and that astrophysics is well integrated into these planet-detection missions.*

The roadmap outlines an ambitious plan of large, expensive, and technologically challenging missions. However, the roadmap contains very little discussion of the current mission costs and technological challenges and milestones that must be met for each mission to be successful. The realism of the proposed mission timeline and the ability of the proposed missions to fit into the budget line are serious concerns. *The panel recommends that broad-based community input be sought to guide decisions if any significant revision to the Search for Earth-like Planets roadmap mission sequence becomes necessary.*

A stronger case could have been made for research and missions that were not a part of the central mission line aimed at the detection of habitable terrestrial planets. The discussion of desired theoretical work is limited, as is the discussion of astrobiology and of the problem of integrated research on planet formation, star formation, and planetary system evolution. As an example, recent research has shown that some extrasolar planetary systems contain gas giants very close to the central star, a configuration very unlike our solar system. An important theme of extrasolar planetary system detection and characterization could be the determination of whether or not our solar system really *is* different from other demographically common solar systems. Appropriate research should focus on gaseous, icy, and water worlds in addition to terrestrial planets. The roadmap has little discussion of the important research on planetary system evolution with the current Hubble and Spitzer missions or that promised by future missions such as SOFIA, the Wide-field Infrared Survey Explorer (WISE), JWST, Herschel, and SAFIR. Similarly, the discussion of ground-based planet detection and characterization activities is limited primarily to the successes of radial velocity surveys, and it fails to include techniques that will be very important during the next decade such as Keck interferometric astrometry (using the Keck outrigger telescopes), other ground-based astrometry, planetary transit photometry, and microlensing observations, as well as detailed study and characterization of planet-host stars and potential TPF target stars. *The panel recommends that NASA construct a balanced program that both seeks Earth-like planets and fosters research on broader issues of solar system formation and evolution in the context of realistic budget constraints and the full suite of facilities and techniques that are appropriate to this line of research.*

The roadmap acknowledges that TPF-I will probably be combined with the European Space Agency development of its Darwin mission, but there is no obvious plan to do this at an early stage. In fact, the roadmap lauds international *competition* rather than cooperation. Truly productive international cooperation must be very carefully fostered and nurtured from the earliest opportunity. The report *U.S.-European Collaboration in Space Science* advocates such cooperation.[23] *The panel recommends that international cooperation be part of the baseline planning for this research.*

Furthermore, the panel concluded that astrobiology was included in both the *Universe Exploration* and *Search for Earth-like Planets* roadmaps as an afterthought and should have been a more integral part of the roadmaps.

CROSSCUTTING SCIENTIFIC ISSUES

There are numerous crosscutting scientific opportunities with other roadmap areas. Taking advantage of these may result in more fruitful science and higher efficiency in the scientific programs. The *Sun-Solar System Connection* roadmap makes the strong case that the Sun and solar system are prime laboratories for fundamental plasma physics, especially magnetic field reconnection.[24] The Stellar Imager has clear implications for stellar astrophysics. The solar heliosphere modulates cosmic rays that affect life on host planets and possibly affect climate through atmospheric ionization and influence on cloud cover. Thus the Interstellar Probe discussed in the *Sun-Solar System Connection* roadmap has obvious relevance to topics of the Universe Division and perhaps Earth science. The solar-system exploration and Mars programs are rife with crosscutting issues in astrobiology, comparative planetology, and the origin and evolution of star and planetary systems.[25,26] The notional Biosignature mission mentioned in the *Earth Science* roadmap is of clear potential astrobiological significance, but was not considered at all in the *Universe Exploration* and *Search for Earth-like Planets* roadmaps, and was not given strong scientific motivation in the *Earth Science* roadmap.[27]

CROSSCUTTING CAPABILITY ISSUES

Most of the capabilities needed to enable the missions presented in these two roadmaps are properly addressed even though these roadmaps did not benefit from the planned integration with NASA's capability roadmaps. The *Universe Exploration* roadmap provides a sound outline of how to organize technology support so that adequate technology exploration and development of enabling technology can proceed to the point at which desired missions can continue on to flight development. This requires investment in research and analysis programs to explore new concepts, including opportunities for proof-of-concept observations from suborbital platforms, and funding for continued engineering development of concepts aligned with mission objectives to bring the technology to spaceflight readiness. Obtaining support for the second step has historically been difficult in the NASA program. *The panel recommends that NASA invest in research and analysis programs to explore new concepts, including opportunities for proof-of-concept observations from suborbital platforms, with particular attention to funding for continued engineering development to bring the technology to spaceflight readiness.*

The *Universe Exploration* roadmap committee explicitly attempted to address "critical" technology needs and "avoided listing 'desirements'" that could replace requirements if they should appear in many roadmaps. Bearing that in mind, the following issues arise:

- Two roadmaps with overlapping capability needs may leave the impression that the development costs are more expensive than is actually the case. The use of different document structures and presentation styles in these two roadmaps makes interpreting the common needs more difficult.
- Little attention is given to the potential use of infrastructure and other capabilities now being planned by the Exploration Systems Mission Directorate. These resources may include in-space

construction by humans or robots and in-space depot and servicing facilities, the availability of which could substantially change the engineering and operational approaches chosen for the missions outlined in the two roadmaps. These capabilities could also enable servicing to extend the useful life of future missions and to permit periodic upgrades of instrumentation. Future in-space capability could also eventually provide in-space integration and testing, thereby avoiding the problems associated with Earth's gravity and atmosphere.

- There is no attention to the timing of the capability development so that there can be high confidence that technical capabilities will be available sufficiently before mission design to allow their full integration.

The panel recommends an assessment of the trade space between launch vehicle lift mass, fairing size, length of mission, aperture size and weight, detector quantum efficiency, and other factors to ensure that the mission options for these two roadmaps are fully understood.

The panel recommends that NASA develop plans to use the long-range technology developed in the Exploration Systems Mission Directorate in service of the goals of the Science Mission Directorate.

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5
Earth Science and Applications from Space

Unlike the other roadmap committees, the committee that produced *Exploring Our Planet for the Benefit of Society: NASA Earth Science and Applications from Space Strategic Roadmap*[1] had no NRC decadal survey to guide it. Past NRC studies have articulated the importance of broad community discussion and input as an essential part of NASA's long-term strategic planning.[2,3] Although the Earth science roadmap committee included representatives from NASA, the National Oceanic and Atmospheric Administration, industry, and academia, much broader community input will be available after completion of the NRC decadal survey in Earth science that is currently in progress and scheduled for completion in 2006. *The panel recommends that the forthcoming NRC Earth science and applications decadal survey be used as a starting point for mid- to long-term planning (i.e., for beyond 2010). Prior to the completion of the decadal survey, NASA planning and advanced technology programs should remain flexible to avoid commitments to missions that might not receive broad community support.* In the near term NASA should focus on the roadmap recommendation that NASA "complete the approved [Earth sciences] program in a timely fashion, including the next Earth System Science Pathfinder Announcement of Opportunity," and on the specific recommendations made in the NRC decadal survey interim report issued in April 2005.[4]

REVIEW OF PROPOSED OBJECTIVES

The Earth science roadmap committee appropriately focused more on Earth science in its own right rather than on studying Earth as a benchmark or testbed for research to be carried out under the vision for space exploration. The roadmap is built around six guiding science questions, all of which have some heritage in previous science strategy documents (e.g., NASA's Earth Science Research Plan and plans for the U.S. Climate Change Science Program). The roadmap rightly focuses on the specific measurements that are required to meet the science objectives, rather than on missions.

The roadmap advocates five separate "lines of inquiry," corresponding to five of the six guiding science questions in the roadmap. These five lines of inquiry largely follow traditional scientific disciplines: atmospheric composition, climate and weather, water, life, and solid Earth. The panel believes that by pursuing a strictly disciplinary approach for the lines of inquiry, NASA may impede advances in areas that are considered to be cross-disciplinary. The sixth science question (What role do human systems play in driving changes in the Earth system?) is treated as a crosscutting issue, and no line of inquiry is proposed for this question.

The selection and sequencing of the scientific objectives are neither thoroughly nor convincingly explained in the roadmap, and there are some serious gaps. Notably, the roadmap omits program elements that are critical to current NASA responsibilities in the Climate Change Science Program, largely in ocean and terrestrial science. As an example, the roadmap's life program encompasses a number of science areas and gives emphasis to biogeochemical cycles. It is responsive to the vision for space exploration, but it omits aspects of land use and land cover change, ecosystems, and biodiversity and their associated measurement needs. The reason for that omission is not explained.

The roadmap defines integration objectives that progress from "exploration and discovery" to "continuous awareness" and "developing perspectives." These are artificial constructs that create confusion. The roadmap also defines a Measurement Maturity Index for space-based measurements, which "encapsulates both the scientific maturity of a measurement and its readiness to transition to operational use."[a] Although the Measurement Maturity Index framework is potentially valuable, it will need considerably more development to be useful in setting priorities for missions. The roadmap discussion of the index does not specify whether all measurement sets are expected to progress linearly and completely through each of the index's stages, or whether there may be measurement sets for which only some of the stages are relevant. In addition, the readiness of a measurement needs to be weighted by the scientific (and societal) importance of the measurement.

Although the roadmap is titled *Exploring Our Planet for the Benefit of Society*, the applications component of the roadmap is inadequately developed. The NRC decadal survey interim report states that "a central responsibility for the coming decade is to ensure that established societal needs help guide scientific priorities more effectively and that emerging scientific knowledge is actively applied to obtain societal benefits."[5] There are several pressing societal issues, such as global food and water security, biodiversity loss, and pollution in coastal zones, that will be exacerbated over the coming decades and that can be informed by NASA science and observations. The applications "lines of inquiry" of the roadmap have yet to be developed, and they need to be closely coupled to both the science and the planned measurements, driven by societal needs, and developed in close communication with the stakeholders. *The panel recommends that as part of long-term planning, NASA develop the applications aspects of its Earth sciences program to a greater degree than was done in the roadmap and strengthen the linkage between the science and applications program components.*

REVIEW OF PROPOSED IMPLEMENTING PROGRAMS

The NASA Earth science roadmap committee assumed that the missions currently in formulation would be implemented, "providing a foundation for the roadmap." As noted by the NRC decadal survey interim report, the delay in some of these missions "jeopardizes NASA's ability to fulfill its obligations" in areas such as climate change research, and the reduced number of Earth System Science Pathfinder (ESSP) missions limits important innovative contributions from the smaller principal investigator-led instruments.[6]

The roadmap's mission timeline advocates a sequential phasing of the five lines of inquiry from exploration to perspective, beginning with atmospheric composition, climate/weather, and water, followed by life and solid Earth. This approach, adopted apparently because of budget concerns and previous investments, is a serious weakness. NASA needs to maintain its scientific inquiry and capabilities in multiple focus areas concurrently. This will allow for continued discovery and will support the integrated view of Earth system science that is unique to the agency.

A closer connection is needed between the science rationale and priority for the proposed missions. For example, the contribution of the Biosignatures mission to Earth science is not articulated.

The goal of the phase-3 implementation stage in the roadmap is to have a fully instrumented observing system in the third decade. However, some components of the observing system are needed now to provide critical ongoing contributions to science (e.g., as recommended by the Intergovernmental Panel on Climate Change) and applications (e.g., via the Global Earth Observation System of Systems). The Earth observing system needs to be designed now and built incrementally, and it needs to be adaptable to incorporate technological improvement.

In order to plan for the types of long-term measurements that are required for climate studies, the roadmap anticipates transitioning measurement techniques from research to operations. If this transition

[a] The Measurement Maturity Index is a counterpart to NASA's longstanding "Technology Readiness Level" index, which represents maturity of a technology for end use.

is to be viable, NASA will need to start by addressing both the current institutional and financial obstacles to transition.[7,8] Similarly, the approach to decision support requires a closer interaction with the stakeholder community.

The roadmap includes plans through 2035. Although such a long planning timeline is needed for other components of the vision for space exploration, such as Mars exploration, there is little point in trying to anticipate the Earth science observation priorities so far in advance. The roadmap foresees some transformational new technologies for the later years of its three-decade planning period, including for example, a blue/green lidar to profile the upper ocean. Such technologies potentially will provide new insights into the Earth system, although at present it would seem premature to predict what breakthroughs might develop in the coming decades. While the roadmap explores a variety of new technologies, broad community input will help in identifying transformational technologies that should be developed for Earth science missions. For example, small satellites could provide important flexibility to the overall program, and the land observation community could consider a constellation of small-satellite imagers to augment the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Operational Land Imager mission.[9] The NRC Earth science decadal survey interim report recommends some additional areas in which enabling technology is needed.[10]

GAPS, OPPORTUNITIES, AND INFRASTRUCTURE

Although the roadmap attempts to capture the breadth of Earth science, there are important measurements that appear to have been neglected, for example, water vapor, air-sea heat fluxes, and land-cover change.

As would be expected, the Earth science roadmap appears to have minimal overlap with the other roadmaps, aside from a shared interest with the *Sun-Solar System Connection* roadmap in examining the relationships between solar variability and climate change, possibly with a flagship mission at the Lagrangian point 1 (L1). The Sun-solar system roadmap, however, appears to assign the L1 mission a secondary priority. The panel cautions that the L1 mission should not be given high overall priority merely because it appears in both the Sun-solar system and Earth science roadmaps. Rather, the relevance of the L1 mission should be thoroughly evaluated for Earth sciences before determining its overall priority. In integrating the roadmaps, NASA will need to balance shared objectives among roadmaps and the resources required to achieve them. The panel understands that the Earth science roadmap committee had little time to explore possible opportunities to share science or technology between roadmaps. The roadmap integration process should identify and evaluate such opportunities.

A number of issues that cut across the many subdisciplines represented in the Earth science roadmap need special attention, particularly with regard to non-satellite infrastructure. For example, the role of data systems and management is addressed only in passing. Given that data management has proved to be a major challenge for NASA in the past, next-generation data management systems need careful consideration within the roadmap and need to be an integral part of mission planning.

The roadmap draws attention to information and computing technology needs and advocates development of systems that merge observations into models through “data assimilation” to provide best estimates of the Earth system. Modern-day weather forecast models depend on data assimilation, and data assimilation systems are now being developed for other aspects of Earth science. Nonetheless, satellite data are important in their own right and not just as inputs to assimilating models. Both model and product validation are crosscutting issues, and product validation needs to be an integral part of the budget planning for each mission.

SCHEDULE, RESOURCES, AND PARTNERSHIPS

The timing of certain missions in the roadmap appears to be delayed relative to the information needs. For example, the Carbon Cycle Strategic Plan in the Climate Change Science Program states that "continued satellite land-cover data products and new remote sensing estimates of above ground biomass will be needed" to carry out carbon monitoring.[11] Given the investment already made in the Vegetation Canopy Lidar, the proposed 2015 launch date for a vegetation structure instrument may need reconsideration. Similarly the proposed mission sequence will result in some immediate and serious gaps in data continuity. For example, the Landsat 7 scan line corrector developed a malfunction in 2003, but its successor, the Operational Land Imager (OLI), is not scheduled for launch until 2010. Without a bridging mission, there will be a serious break in land data continuity.[12]

The near-term technological development appears to be realistic, but there is insufficient detail in the roadmap to permit an in-depth evaluation. For example, the rationale and technological approach for the Cal/Val mission need further elaboration. The out-year missions are not well enough developed to evaluate their technological feasibility.

The Earth science roadmap assigns missions to single lines of inquiry, even if mission measurements are relevant to more than one line of inquiry. For example, the Orbiting Carbon Observatory is listed as an atmospheric composition mission but could also be considered a climate mission and a life mission. This narrow focus could exclude ancillary science if requirements for broader science questions were not considered early in the design phase.

Unlike with the other roadmaps, the near-term missions and the budget implications or trade-offs between the different missions were not discussed in the Earth science roadmap. The science community needs to be aware of the potential costs of different missions and to be involved in the discussion of trade-offs between larger and smaller missions and the associated science implications.

The roadmap is essentially a NASA-alone plan, aside from the stated intent to transfer mature observational methods to operations. Interagency cooperation is critical for ensuring long-term operational measurements, and an ongoing dialogue concerning mission planning will be needed with NOAA, which plays a strong role in atmospheric and ocean observations.[13] NASA could utilize the Climate Change Science Program Observation Working Group for mission planning in an interagency context. International cooperation also will be important in implementing and enhancing the NASA program. The roadmap does not explore the opportunities that are afforded to NASA by international cooperation in Earth observation via the Committee on Earth Observation Satellites and the emerging Global Earth Observation System of Systems (GEOSS) and the final plan from the Interagency Working Group on Earth Observation.[14,15]

SCIENTIFIC RESEARCH SUPPORT FOR THE VISION FOR SPACE EXPLORATION

The NRC panel was also tasked with evaluating how the Earth science roadmap provides scientific research support for the vision for space exploration. The panel recognizes that the Earth science roadmap is distinctly different from the space science roadmaps. Earth and space science have different histories in NASA. The Earth science roadmap is not strongly coupled to the exploration objectives, but it does directly respond to the NASA goals "to improve life here" and "to know our origin and destiny."[b] Earth science at NASA also has a number of external pressures on its near- and mid-term planning, including the requirement to contribute to a number of national imperatives such as the Climate Change Science Program, the Interagency Working Group on Earth Observation, the Commercial Remote Sensing and the Land Remote Sensing Space Policies, and international commitments such as the Intergovernmental Panel on Climate Change and GEOSS. The breadth of NASA's multidisciplinary

[b] M. Allen and P. Hertz, "NASA Roadmaps and Science Integration," presentation to Review of NASA Strategic Roadmaps: Science Panel, Washington, D.C., June 13, 2005.

Earth science program is greater than that of the programs covered by the other roadmaps, and there is the additional challenge of addressing both science and applications.

Recognizing the strong message from the NRC decadal survey interim report that "NASA must retain Earth science as a central priority, to support critical improvements in understanding the planet and developing useful applications,"[16] *the panel recommends that NASA strongly support the Earth science program independent of its involvement in the vision for space exploration.*

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6
Sun-Solar System Connection

The *Sun-Solar System Connection* roadmap is a well thought out document that succeeds in placing many Sun-solar system science objectives into the context of the vision for space exploration.[1] The roadmap correctly notes that the Sun-solar system science program has reached a level of maturity such that the focus has become "systems science" that addresses the strong interactions between all of the different components of the Sun-solar system environments such as the Sun, interplanetary medium, near-Earth and near-planet space environments, upper atmospheres, and heliosphere, even while essential work continues on the individual constituents. Such a systems approach was already required in the preexploration visions era to address Living with a Star and other near-Earth space environment studies, and it is also now needed to address the issues of developing and protecting exploration infrastructure and astronauts.[2] The roadmap has made adjustments to accommodate resources and to support the exploration schedule; however the resulting overall priorities are roughly consistent with the key Sun-solar system-related NRC decadal survey *The Sun to the Earth—and Beyond*.[3] This outcome was anticipated with a follow-on NRC study, which reexamined the NRC decadal recommendations in the context of the exploration objectives.[4]

At the highest level the panel generally supports the science and implementation program developed in the roadmap. However, the roadmap suggests that the rationale depends much more strongly than necessary on a utilitarian requirements flowdown and "system science," and thus it could be construed as undervaluing the role of fundamental discovery science. The panel identifies gaps that result from such a strictly utilitarian flowdown, suggests greater consideration of partnerships that can help fill gaps, and identifies shortcomings in the consideration of infrastructure maintenance. Although the panel understands that the roadmap document itself will not be updated according to recommendations given here, the panel does offer recommendations as to how the Sun-solar system science program should be articulated and organized in future NASA promulgations and planning activities, including the upcoming exercise to integrate the different NASA science discipline roadmaps.

INTRINSIC MERIT OF THE SUN-SOLAR SYSTEM CONNECTION ROADMAP SCIENCE PROGRAM

The NRC decadal survey in solar and space physics declares that the study of solar and space physics is "motivated by the deep-seated human impulse to know and understand the workings of Nature."[5] The impact of the study of these "workings of Nature" is leveraged dramatically by the extent to which the findings affect other disciplines and ventures. Specifically, the survey report and others go on to emphasize the importance of these investigations for understanding all solar system bodies, including our Earth, as well as astrophysical objects lying well beyond the reach of the Sun's influence, where the same physics arises but is not directly observable, and the impact of such investigations on the study of the formation of solar systems and planetary systems, as well as the habitability of planetary systems.[6,7] These reports point out that the fundamental physics of many important processes with wide application to laboratory and astrophysical plasma systems, for example, magnetic reconnection, are best addressed in the naturally occurring plasma environments available in the Sun-solar system domain.

The *Sun-Solar System Connection* roadmap begins with a statement of its overriding objectives, which are specifically to (1) open the frontier to space weather prediction, (2) understand the nature of our home in space, and (3) safeguard our outward journey. The roadmap's articulation of these objectives is based almost entirely on the applications of the science, even in justifying the investigation of the most fundamental processes. These largely utilitarian objectives flow down to research focus areas. Examples include "understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storm" and "understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment."[8] These focus areas have high intrinsic science merit. They are derivable from previous articulations of Sun-solar system goals before the advent of the exploration program.[9,10] With the exception of some gaps, discussed below, the panel strongly endorses these focus areas. However, by justifying these objectives so strongly on the basis of their role in enabling the vision for space exploration and other utilitarian goals, the roadmap arrives at a science program that may not be robust to changes in the exploration vision and that in part releases NASA from its longstanding stewardship responsibilities of what the panel believes is a scientific endeavor that has high intrinsic merit irrespective of its important practical applications for achieving the exploration objectives. NASA has stewardship for this science program because progress in the Sun-solar system discipline relies overwhelmingly on space systems for obtaining measurements and because of NASA's long-term investment in these areas.

The panel strongly recommends that the connections of the Sun-solar system objectives and focus areas to the aspects of the Sun-solar system discipline with the highest scientific merit be articulated and maintained in any future promulgation of the Sun-solar system science and implementation program. This recommendation is not meant to replace the utilitarian flowdown; the "intrinsic scientific merit" flowdown is complementary. The panel also notes that the overwhelming reliance on a utilitarian flowdown can lead to gaps in the science program over which NASA has had, and should continue to have, stewardship.

GAPS, CROSSCUTTING ISSUES, AND INFRASTRUCTURE

The system science approach described above, whereby the sun-heliosphere-planetary atmospheres ensemble is studied as an integrated whole, requires simultaneous, coordinated measurements of many parameters at many places. The individual elements of the *Sun-Solar System Connection* roadmap tackle the fundamental physical processes, but the study of the integrated system can best be achieved if the individual assets operate together, as a system. The baseline roadmap plan spreads the elements out over time to such an extent that this necessary synergy risks being lost. *The panel recommends that every effort be expended to better achieve the needed synergies between the different elements enabled by simultaneous observations from multiple locations and observing perspectives.*

In addition to trying to identify additional resources so that the more robust flight programs identified by the roadmap can be implemented, *a stronger integration of non-NASA activities than that present in the roadmap should be pursued.*[11] Discussions of partnerships that NASA must have, or should develop, with the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the Department of Defense (DOD), and potentially with the Department of Energy (DOE) are not developed to the extent that they could be, given the scientific and programmatic potential.[12] For example, the study of Earth's ionosphere-thermosphere regions would be seriously deficient without the support of the NSF and DOD, and NOAA is the eventual intermediate customer, and eventual operator, of the space-weather predictive capabilities that are being developed as part of the Living with a Star program. The monitoring of the solar wind plasma and fields at the L_1 position, between the Sun and Earth, is a good example of measurements that are essential for space weather operations and thus could be transitioned to NOAA.

Partnerships with other countries, in particular with the European and Japanese Space Agencies, can help to increase the simultaneous coverage over more of the connected system.[13] For example, the

European Space Agency's (ESA's) Solar Orbiter mission could provide the simultaneous imaging of the solar source region for the solar wind plasma and energetic particles measured by NASA's Inner Heliosphere Sentinels. ESA's SWARM mission could provide limited ionosphere-thermosphere overlap with NASA's Solar Dynamic Observatory.

Partnerships with the other NASA discipline areas are also important and need to be explored further. There is a strong ongoing partnership with solar system exploration because the space environment is an integral part of planetary systems, with missions such as Voyager, Cassini, and the newly selected Juno carrying a complement of space physics instrumentation. The Sun-Earth system is the model for searches for Earth-like planets and habitable environments, and the Sun-solar system flagship mission, Stellar Imager, is devoted to resolving nearby stars, while the Interstellar Probe will provide in situ samples of the universe beyond the solar system. An L1 Earth-Sun joint mission with Earth sciences, with simultaneous solar and terrestrial observations, could be potentially rewarding but requires detailed study.

The panel recommends that NASA proactively incorporate all of the partnership opportunities listed here in its planning activities to maximize the synergies in the measurement of different regions.

The issue of the relative scarcity of missions in any one subdiscipline (solar, magnetospheric, and so on) also affects the infrastructure needed to sustain the science and technology necessary to achieve the roadmap objectives. Typically, Sun-solar system scientists develop most of their flight instrumentation, often in small university groups, and thus they are particularly vulnerable to a low mission flight rate and the diminishing suborbital program. Under the present program and the "realistic" Sun-solar system roadmap program, the survival of these groups would be jeopardized. *The panel recommends that the issue of research group infrastructure be better incorporated into future promulgations of the Sun-solar system plans.* The partnership opportunities discussed above can play a significant role here.

The large-scale structure of the heliosphere and the interaction with the interstellar medium are not well addressed in the roadmap, and the Interstellar Probe flagship mission receives scant mention. In addition, the truly transformational, fundamental discovery science offered by the other flagship missions (Solar Probe, Stellar Imager), and by future Explorer missions developed as the requirements and opportunities arise, also appears as an orphan in the roadmap, achievable only by significant programmatic growth. Because of the importance that the panel places on the fundamental science in generating a science plan, while recognizing the importance of utilitarian objectives as well, *the panel recommends that the need to address the science of these transformational missions, as well as fundamental physical processes of individual components of the system, be more prominently articulated in future promulgation of the Sun-solar system science objectives and implementation plan.*

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7
Crosscutting and Integration Issues

Taken together, the six roadmaps reviewed by the panel demonstrate vibrancy and excitement and show great promise. Such defects as were identified during the panel's review are, in the main, the result of the very brief time allotted by NASA for the roadmap committees to do their work.

Accordingly, the roadmap committees were not able to draw on the broadest possible inputs from the entire science community or spend the time in deliberations typical of the NRC decadal survey process (decadal surveys take approximately 2 years to complete) or have sufficient opportunity for interaction among the various planning activities going on in parallel. The strategic roadmaps also did not have the benefit of an external review process, again in contrast to the extensive in-depth review process to which NRC decadal surveys are subjected.

The panel was struck by the relative paucity of crosscutting activities and issues identified in the individual roadmaps. The two examples below are intended solely as illustrations of the kinds of issues that need to be considered in the integration process, and not as an indication of priorities:

- *Use of exploration infrastructure.* The panel believes that the science roadmap committees did not adequately consider the potential use of capabilities now being planned or considered by NASA's Exploration Systems Mission Directorate (ESMD). For example, such capabilities might include in-space construction and servicing by humans or robots, which could substantially change the engineering and operational options available for the missions outlined in the science roadmaps. Such servicing could potentially extend the useful life of future missions and allow for periodic upgrades. An obvious example of these benefits, described in a recent NRC report,[1] derives from the Hubble Space Telescope experience. Large telescopes being used for the universe missions or Earth-like planets missions potentially could be made more economical through periodic instrument upgrades and replacement of components either by humans or robots, extending the lifetime of an astronomical observatory significantly beyond that planned for currently expendable spacecraft. ESMD in-space capability also eventually could provide in-space integration and testing, thereby avoiding the limits associated with Earth's gravity and atmosphere. This, in turn, could enable a new generation of large optical systems without many of the scalability limits that now exist. Although this example is intended to be illustrative only, the panel believes that it indicates how new opportunities exist in the exploration program that can be exploited by the science program. The NRC has previously stated that exploration, properly done, is science,[2] and the panel thinks that exploration, properly done, can benefit science in myriad ways. The panel urges NASA management to ensure that an effective flow of requirements on these topics occurs from the Science Mission Directorate to ESMD and that, to maximize efficiency, infrastructure planning in ESMD be influenced by these requirements.
- *Synergism between the science goals for lunar and for martian exploration.* Although the Mars roadmap urges that the definition of lunar science be derived from the needs of martian research, the panel notes that the Moon also is a scientific target of significance in its own right. The Moon is an important location for characterizing conditions in the very early solar system, and its properties should be better understood independent of goals for Mars. To engage in a lunar science program that derives strictly from goals for Mars exploration is too narrow a focus. Equally too narrow is a program of lunar research that concentrates only on characterizing the surface resources, safety issues, and environmental

factors pertinent to human exploration. A balanced program of benefit to both the science and the exploration communities is required. To this end, NASA management should ensure that there is an effective flow of communication between the lunar and Mars programs on scientific, technical, and infrastructure issues and that the science community is thoroughly engaged in the definition of the missions that will be conducted.

The Moon can be a platform for conducting nonlunar science, possibly through the use of antennas and telescopes, measurement of radiation environments, and other types of science. The panel urges NASA, as part of the strategic planning activities, to pay special attention to issues that span more than one of the roadmaps.

PRINCIPLES OF INTEGRATING SCIENCE STRATEGIC ROADMAPS

We live in an extraordinarily rich age of scientific discovery and opportunity. The exploration vision has opened the time horizon so that the plans are not limited by the immediate fiscal years but extend more than a generation into the future. Unfortunately, available resources are, and are likely to be, limited. It is in this context of extraordinary opportunity, and an expanded time horizon for planning, that guiding principles are needed for setting priorities in NASA's integrated plan for space and Earth science research. This report follows an earlier report from the Space Studies Board titled *Science in NASA's Vision for Space Exploration*.[3] That report, prepared and issued while the NASA strategic roadmap planning effort was just beginning in early 2005, developed a set of guiding principles to assist NASA in making decisions affecting the overall science program in the context of the president's space exploration initiative.

The six roadmaps reviewed in the present report represent inputs to NASA's strategic planning process rather than finalized documents presenting agency policy. The panel, in addition to reviewing each of the roadmaps individually, considered the principles that should be used for prioritization and integration, leading to an overall space and Earth science exploration program spanning more than two decades. These principles are an expansion and amplification of the principles noted in *Science in NASA's Vision for Space Exploration*. NASA should apply the guiding principles below in integrating the exciting scientific promise evident in the strategic roadmaps into a robust, coherent, enduring science program that will serve the nation now and for future generations.

Advancing Intellectual Understanding

Scientific merit, as measured by the capability of advancing intellectual understanding of the cosmos and our place in it, should be a guiding principle in planning. The goals and objectives set forth in relevant NRC decadal surveys and similar reports should be the primary criteria for setting priorities and program content. The survey process has become a well-established way of providing broad-based, intellectually rigorous input to NASA. This process has been one of the foundations that has enabled NASA to develop an outstanding science program with a long and successful record to its credit. These surveys have always striven to identify the most important, revolutionary science that should be undertaken and, as such, have set a high bar of excellence. The NRC decadal surveys have benefited from the broad inputs by the science community and are recognized for their credibility and stability. Science that is enabled by exploration should be held to the same standard of scientific merit and advancing intellectual understanding as the science goals embodied and recommended in past NRC decadal surveys. As the capabilities of the space exploration initiative develop, the appropriate distribution of research between humans and robots also will have to be weighed in regard to that standard.

A direct implication of applying the standard of advancing the intellectual understanding of the universe around us when making decisions about the content of a robust space exploration program is that such a program should pursue exploration in a broad rather than a narrow sense. This approach was explicitly recommended in the report *Science in NASA's Vision for Space Exploration*.[4] That report urged that targets for exploration should include the Earth where we live, the objects of the solar system where humans may be able to visit, the broader solar system including the Sun, and the vast universe beyond, and that the targets should be those that have the greatest opportunity to advance our understanding of how the universe works, who we are, where we came from, and what our ultimate destiny is. An exploration effort that falls short of such a comprehensive perspective risks undermining the broad strengths that NASA's science programs have developed to date. For example, a recent letter report[5] on progress in astronomy and astrophysics toward meeting the goals of the most recent decadal survey[6] noted serious concerns over near-term effects that are already being experienced owing to NASA's decisions to accelerate certain advanced mission concepts at the expense of a broader program that follows the priorities of the decadal survey. As a second example, the report *Earth Science and Applications from Space: Urgent Issues and Opportunities*[7] sounded the alarm about the effects of program cancellations, reductions in scope, or deferrals that appear to be driven by major shifts in NASA priorities toward implementing the vision for space exploration.[a]

Program Span, Diversity, Stability, and Flexibility

The integrated science program constructed by NASA should have characteristics such that all major scientific disciplines can make progress toward their goals as established in NRC decadal surveys or other similar reports. Decisions at the decision or option points noted in the various roadmaps will benefit greatly from the broad science community's involvement in the decision process. No discipline represented by the six strategic roadmaps should be allowed to dominate or wither, because they are all interrelated. The program should be discovery driven and not rigid, allowing exciting new discoveries to be rapidly accommodated within a program plan. Flexibility is enhanced by having a mix of small, highly responsive missions as well as flagship missions that may take the better part of a decade to complete. The mix of missions also provides opportunities for the training and development of scientists and engineers.

Creating Opportunities for the Future

The challenge for NASA, and the nation, is to build a space exploration program that transcends the current generation of scientists and engineers. A robust, sustainable aerospace community is required. Investing in the intellectual foundation and physical infrastructure of the nation that provide the basis for the capability of space exploration—and in the stewardship of that infrastructure—is a daunting but essential task if we are to continue to be a space-faring nation.

Explicit strategies for developing the next generation of space scientists and space engineers—and the generation after that—are needed. Spanning public outreach and education, these strategies need to have a scope commensurate with the scope of the vision for space exploration.

A reasonably stable space research and space engineering community is necessary for the realization of the full scope of the exploration vision. If stable funding is not available, the research community may not remain involved in, or may disengage from, specific fields that will eventually be critical—either for realizing the vision for exploration or for advancing the various disciplines of space sciences and Earth observation. Research and analysis programs, theory programs, and rocket- and

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[a] Specifically, the report stated, "Opportunities to discover new knowledge about Earth are diminished as mission after mission is canceled, descoped, or delayed because of budget cutbacks, which appear to be largely the result of new obligations to support flight programs that are part of the administration's vision for space exploration" (p. 1).

balloon-based research programs provide the training and experience base at our universities and research institutes and will serve to develop the next generation of scientists and engineers. These programs need to be evaluated, judged, and prioritized using the same high standards applied to initiatives described in NRC decadal surveys and endorsed by the panel, but they must be integrated into the overall program.

A continuing, vigorous development of technology is necessary for the success of the exploration program. Advanced technology needs should be assessed, prioritized, and properly funded so that technologies with long lead times can be developed in time to reduce mission technical risk as well as schedule and cost risk. Multiple-use technologies—technologies applicable to several branches of the space sciences, for example, spanning several of the science disciplines addressed by the roadmaps—should receive special consideration.

Capabilities to handle the communications and data transmission and storage and archive loads of space exploration require assessment and appropriate investment for timely implementation. Five of the six roadmaps reviewed expressed a need for the upgrading of the Deep Space Network functionality. Although individual roadmaps differed concerning specific requirements, the panel found common themes: needs for increased downlink data rates and improved data access, distribution and management, storage, archiving, and retrieval. The NASA roadmap integration and strategic planning process should consider these needs as a vital part of developing the space exploration initiative infrastructure.

The NRC decadal surveys and similar reports have already proved useful for defining near-term mission priorities. These decadal surveys also can be used to define near-term technology investments. Planning for missions that extend past the time horizon of the decadal surveys should be accompanied by appropriate technology investments.

Amplifying the Span, Reach, Impact, and Strength of the NASA Exploration Program

This review of the NASA strategic roadmaps suggests that there is much to be gained by enhancing the connections with other agencies of the executive branch that have responsibilities or interests in space research and space technology. These agencies include NOAA, DOD, DOE, and NSF. Although elements of cooperation and coordination are already in place, the time horizon and scope of the exploration vision are so extraordinary that a fundamental reexamination of existing arrangements seems to be called for. In particular, the impact of space research now transcends the space science community and involves nonscientists—witness the impact of the space-based Earth sciences on agriculture, fisheries, and a host of other enterprises and activities at the commercial, industrial, and state level. Reinvigorating the transition from space research to operations—typically from NASA to NOAA—and enhancing the ultimate use of space data by a host of enterprises should be important goals. These goals suggest the importance of early involvement of other stakeholders (operations as well as applications) besides NASA in the formulation of exploration programs relevant to the interests of these other actors.

International Cooperation and Coordination

In many areas of space science there is a rich heritage of cooperation with other space-faring nations. Such cooperation has proved extremely fruitful in maximizing the science returns from space missions.

NASA has had a decades-long history of international cooperation in space activities—both in crewed space programs and in uncrewed science missions. Furthermore, many national space agencies around the world have committed significant resources over the years to cooperation with NASA programs. This cooperation has been a valuable contributor in providing a platform for displaying U.S. scientific and technological prowess. Space cooperation has provided direct scientific benefits to both the United States and the other cooperating nations. Although it recognizes that international cooperation can have its negative aspects as well, the panel believes that the subject is worthy of greater attention in NASA scientific strategic planning than it has received in these roadmaps.

The extraordinary scope of the space exploration vision and the multigenerational span of this initiative provide an opportunity for the United States to seek out partners from other nations to join in this grand adventure. The panel recognizes that, as has been pointed out in previous NRC reports,[8,9] current implementation of International Traffic in Arms Regulations (ITAR) continues to be a serious impediment to international cooperation; however, the overwhelming imperative of the space exploration initiative—and the president's invitation for other nations to join this endeavor—demand a renewed effort to ameliorate the effects of ITAR so that its goals can be obtained without unduly affecting NASA's efforts in international cooperation with foreign partners.

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Appendixes

A
Letters from NASA

National Aeronautics and
Space Administration
Office of the Administrator
Washington, DC 20546-0001

July 12, 2004

The Honorable Bruce Alberts
President
National Academy of Sciences
500 Fifth St., NW
Washington, DC 20001

Dear Dr. Alberts:

The recently completed Report of the President's Commission on Implementation of United States Space Exploration Policy ". . . recommends that NASA ask the National Academy of Sciences to engage its constituent scientific community in a re-evaluation of priorities to exploit opportunities created by the space exploration vision. In particular, the community should consider how machines and humans, used separately and in combination, can maximize scientific returns." NASA believes that such engagement would be beneficial and continue a rich tradition of cooperative endeavor between our Agency and the Academy.

As a consequence, I propose that a NASA senior leadership team meet with the National Academy of Sciences and the National Academy of Engineering to consider how we might collectively address the Commission's recommendations. Dr. Charles Elachi, Director of NASA's Jet Propulsion Laboratory, will lead the team for NASA.

I look forward to our discussions regarding this exciting aspect of implementing the President's Vision.

Cordially,

Sean O'Keefe
Administrator

National Aeronautics and
Space Administration

Headquarters
Washington, DC 20546-0001

Science Mission Directorate

December 21,2004

Dr. Lennard Fisk
Chair
Space Studies Board
National Research Council
500 5th Street, NW
Washington, DC 20001

Dear Dr. Fisk:

In January 2004, President Bush directed NASA to pursue a broad but focused program of space exploration. In response to this direction, and subsequent guidance from the Aldridge Commission, NASA has laid out a planning framework that will culminate in an agency-wide Integrated Space Architecture implementing this Vision for Space Exploration. This Architecture will be constructed from Strategic Roadmaps and Capability Roadmaps prepared over the next six months. The Architecture will be used to guide agency-wide programmatic and budget decisions.

The Strategic Roadmaps to be developed in support of this integrated planning process will refine top-level Agency Objectives flowing from the Vision for Space Exploration and propose implementation options, pathways, and decision processes for achieving these strategic objectives. Thirteen advisory committees have been chartered under the Federal Advisory Committee Act to develop these Roadmaps. Each committee includes representatives from industry, academia, NASA, and other Government agencies. The schedule for completion of these roadmaps varies, but most are projected for completion by the end of July.

Because of the critical importance of the Architecture, and, therefore, of the Roadmaps upon which it is based, NASA would like to request that the Space Studies Board, working together with the Aeronautics and Space Engineering Board as appropriate, conduct a critical review of drafts of eleven of these roadmaps as they reach a mature state. A review of the other two roadmaps, on aeronautical technologies and space shuttle, will be undertaken separately. The schedule and terms of reference of the review requested here are delineated in the enclosed Statement of Work.

We look forward to working with you and your colleagues to ensure the success of NASA's planning activity and the resulting exciting program of exploration.

Cordially,

Bernard Seery
Director
Advanced Planning and Integration Office

Enclosure

National Aeronautics and
Space Administration
Office of the Administrator
Washington, DC 20546-0001

April 28,2005

The Honorable Shenvood L. Boehlert
Chairman
Committee on Science
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

As NASA implements the Vision for Space Exploration, we recognize the magnitude of the task ahead and the importance of engaging the best and the brightest the country has to offer in developing the requisite details for an effective implementation.

In two letters dated December 10,2004 and December 23,2004, NASA notified the Committee of the establishment of 13 Strategic Roadmap Committees chartered to advise the NASA Administrator on a range of areas related to the Vision for Space Exploration and the Mission of the Agency. These Committees were chartered under the Federal Advisory Committee Act (FACA) (5 U.S.C. App.). NASA also established 15 Capability Roadmap Teams that have worked to identify key capabilities needed to support the Agency's investment portfolio as we strive to reach our science and exploration goals.

For many months, teams of outstanding individuals have played an important role in helping craft roadmaps for NASA. Recognizing that broad participation in the process that informs critical space program decision-making is extremely important, NASA structured the roadmap teams to include individuals who are considered experts in their fields from within NASA, other government agencies, academia, and the private sector. We appreciate their hard work and support and value their contributions to this critical endeavor.

To best use these roadmaps to inform our fiscal year 2005 Operating Plans, fiscal year 2006 budget plans, and fiscal year 2007 budget development, NASA is accelerating the completion of roadmap development and creating a strategic architecture. This decision-making framework must be available to NASA leadership by mid-summer 2005 to influence major programmatic decisions as part of the fiscal year 2007 budget development and ensure that current budget plans are aligned with the new direction.

The roadmaps developed by these experts will provide an excellent foundation for NASA integration of these roadmaps into a decision-making framework. We will give full consideration to their thoughtful contributions as we finalize the NASA architecture to support our future missions, programs, and budget requests.

Given our decision to accelerate the schedule, NASA will complete all roadmap efforts – strategic and capability – by May *22, 2005*. This revised schedule, with an architecture development effort beginning immediately, impacts the National Research Council (NRC) review of individual roadmaps, which will not take place as originally planned. The NRC, in response to separate congressional direction to review NASA science, will receive the science strategic roadmaps and will provide a report or other input to NASA by August 1, *2005*. We look forward to receiving the NRC's recommendations on the science roadmaps and to a continuing dialogue on science priorities and related issues.

To support immediate decision-making, NASA is initiating an internal Exploration Systems Architecture Study (ESAS) to determine how to accelerate development of the Crew Exploration Vehicle (CEV) and reduce the gap between Shuttle retirement and CEV operations. NASA will select a preferred architecture approach this summer for lunar exploration, including CEV launch, in-space transportation, and surface operations, and develop associated requirements and budgets for implementation. This architecture study is to support the Agency's science and exploration objectives.

We would be pleased to discuss these planning efforts and the new schedule in more detail at your convenience. Questions may be directed to the Acting Assistant Administrator for Legislative Affairs, Angela Phillips Diaz, at *(202)* 358-1948.

Cordially,

Michael D. Griffin
Administrator

B
Acronyms and Abbreviations

AAp	*Astronomy and Astrophysics in the New Millennium*
DOD	Department of Defense
DOE	Department of Energy
DSN	Deep Space Network
ESA	European Space Agency
ESMD	Exploration Systems Mission Directorate
EUV	extreme ultraviolet
GEO	geosynchronous Earth orbit
GEOSS	Global Earth Observation System of Systems
GLAST	Gamma-ray Large Area Space Telescope
HST	Hubble Space Telescope
ITAR	International Traffic in Arms Regulations
JDEM	Joint Dark Energy Mission
JWST	James Webb Space Telescope
L1	Lagrangian point 1
LEO	low Earth orbit
LISA	Laser Interferometer Space Antenna
MEM	Mars Environment Mission
MEO	medium Earth orbit
MEPAG	Mars Exploration Program Analysis Group
MSL	Mars Science Laboratory
MSR	Mars Sample Return
MTO	Mars Telecommunication Orbiter
NASA	National Aeronautics and Space Administration
NIR	near infrared
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRC	National Research Council
NSF	National Science Foundation
OLI	Operational Land Imager

PTL	Pathways to Life
SAFIR	Single Aperture Far-Infrared
SIM	Space Interferometry Mission
SOFIA	Stratospheric Observatory for Infrared Astronomy
TPF-C	Terrestrial Planet Finder-Coronograph
TPF-I	Terrestrial Planet Finder-Interferometer
UV	ultraviolet
Vis	visible
WISE	Wide-field Infrared Survey Explorer

C
Biographies of Panel Members and Staff

GEORGE A. PAULIKAS, *Chair*, retired after 37 years at the Aerospace Corporation, having joined Aerospace in 1961 as a member of the technical staff and later becoming department head, laboratory director, vice president, and senior vice president. He became executive vice president in 1992. He received the company's highest award, the Trustees' Distinguished Achievement Award, in 1981 in recognition of research leading to a new understanding of the dynamics of space radiation and its effect on spacecraft. Dr. Paulikas' other awards and honors include the Jimmy Doolittle Fellowship Award, the National Reconnaissance Office Gold Medal, the Air Force Space Division Award for Excellence, and the Air Force Meritorious Civilian Service Medal, both in 1981 and 1986. Dr. Paulikas is vice-chair of the NRC Space Studies Board. He has also served on a number of NRC review committees, including the Committee on the Scientific Context for Space Exploration, Committee on Systems Integration for Project Constellation, Workshop Committee on Issues and Opportunities Regarding the Future of the U.S. Space Program, and the Committee to Review the NASA Earth Science Enterprise Strategic Plan.

RETA F. BEEBE is a professor in the Astronomy Department at New Mexico State University, Las Cruces, and a member of the Space Studies Board. Dr. Beebe's research activities involve the study of the atmospheres of Jupiter and Saturn and, in particular, studies of cloud motions and evolution in Jupiter's atmosphere. She is the author of several books and articles concerning telescopic observations of the giant planets, including *Jupiter: The Giant Planet*. Dr. Beebe manages the Atmospheres Discipline Node and is project scientist of NASA's Planetary Data System, and she was a member of the Galileo imaging team and lead scientist for the team using the Hubble Space Telescope to provide context images for the Galileo project. She is the former chair of the American Astronomical Society's Division for Planetary Sciences and was a member of the NRC Committee on Planetary and Lunar Exploration (COMPLEX). Dr. Beebe now serves as chair of COMPLEX, and she chaired the Solar System Exploration Survey's Giant Planets Panel.

WENDY M. CALVIN is a research associate professor at the Arthur Brant Laboratory for Exploration Geophysics, University of Nevada, Reno, using infrared spectroscopy in research that emphasizes characterizing the nature and association of water, volatile ices, and minerals to better understand physical and chemical processes occurring in a variety of planetary and space environments. Her current research includes studies of alteration minerals and ices on Mars to understand climate history and variability and volatile element transport and sequestrations. She is a participating scientist on the Mars Exploration Rover and is on the MARCI camera team on the Mars Reconnaissance Orbiter. Dr. Calvin was a member of the NRC Committee on Planetary and Lunar Exploration and the Committee on the Astrophysical Context of Life.

WILLIAM D. COCHRAN is a senior research scientist in the McDonald Observatory at the University of Texas, Austin. His research interests include searches for extrasolar planetary systems; high-precision measurements of stellar radial-velocity variations; and studies of variable stars, asteroids, planetary atmospheres, and comets. A leader in the study of planetary systems, Dr. Cochran is a co-investigator on NASA's Kepler mission and has served as chair of the Division for Planetary Sciences of the American

Astronomical Society. Dr. Cochran currently serves on the NRC Committee on Planetary and Lunar Exploration, the Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion: A Vision for Beyond 2015, and the Panel on Astronomy and Astrophysics.

EDWARD FRIEDMAN has been with the Boeing Company's NASA Program area since 2000 and was selected as a Boeing Technical Fellow in 2001. Dr. Friedman provides technology support to teams pursuing both large and small NASA space science and exploration opportunities. He led the Boeing Terrestrial Planet Finder contract. Dr. Friedman is a member of the engineering teams for the infrared telescopes SPIRIT, SPECS, and SAFIR. From 1993 to 2000, he was Ball Aerospace's chief technologist in the civil space business unit, with an emphasis on planet detection technologies and systems. His specialties include systems engineering and architectures for space telescopes, the role of humans and robots in telescope assembly, design/modeling tools, imaging systems/optical components, interferometry/formation flying, and cryogenic systems. As an adjunct professor of electrical engineering at the University of Colorado, he led a student's successful pursuit of a Ph.D. in adaptive optics. He is the author of three books on electro-optics technology.

SARAH T. GILLE is an associate professor at the University of California, San Diego, in the Scripps Institution of Oceanography and in the Department of Mechanical and Aerospace Engineering. Her research interests are in climate and ocean dynamics. She interprets satellite observations from altimetry and scatterometry, with the goal of understanding physical processes controlling ocean climate. She is a member of the NASA Jet Propulsion Laboratory (JPL) Ocean Vector Wind Science Team and the NASA JPL Jason Science Working Team. Dr. Gille previously served on the NRC Committee on Earth Studies and the Committee to Review the NASA Earth Science Enterprise Strategic Plan.

JOHN HAAS is the New England division manager for Applied Research Associates, located in South Royalton, Vermont. Dr. Haas is currently working on the development of sensors and analytical methodologies for process, environmental, biotechnical, and geotechnical monitoring applications, including planetary exploration. Dr. Haas received his Ph.D. in analytical chemistry from the University of Massachusetts and has been principal investigator on nearly two dozen research programs in the areas of field analytical chemistry instrumentation, detection of chemicals of concern to human health, sensor development, geochemistry/geophysics, in situ sampling and measurement techniques, remote fiber-optic sensing, laser spectroscopy, and miniature devices. Among his achievements are the invention of various Raman, fluorescence, absorbance, and refractive index fiber-optic probes, a miniature fluorescence sensor, and a unique Raman spectrograph. Dr. Haas has also developed an array of small chemical, radiation, and geophysical sensors and samplers for use in the cone penetrometer, a subsurface geophysical and geochemical characterization tool. In 2002, he served on the NRC committee that produced the report *Safe on Mars*.

MICHAEL G. HAUSER is the deputy director at the Space Telescope Science Institute and adjunct professor in the physics and astronomy department at Johns Hopkins University. His research interests are infrared astronomy, cosmology, the interplanetary medium, and the interstellar medium. Dr. Hauser is a member of the American Association for the Advancement of Science (fellow), the American Astronomical Society, the American Physical Society (fellow), the International Astronomical Union, and Sigma Xi. Dr. Hauser is the recipient of numerous honors and awards, including the NASA Exceptional Scientific Achievement Medal, 1984 and 1991; the John C. Lindsay Memorial Award (Goddard Space Flight Center), 1986; and the Senior Executive Service Meritorious Executive Award, 1994. He was a science team member of NASA's IRAS and COBE missions, and principal investigator of the COBE Diffuse Infrared Background Experiment. Dr. Hauser served as a member of the NRC Panel on Astronomy Education and Policy of the Astronomy and Astrophysics Survey Committee and as a member of the Steering Committee for the Task Group on Space Astronomy and Astrophysics.

CHRISTOPHER O. JUSTICE received his Ph.D. from the University of Reading, United Kingdom. Since 2001 he has been a professor and research director in the Geography Department of the University of Maryland. He is a team member and land discipline chair of the NASA Moderate Imaging Spectroradiometer (MODIS) Science Team and is responsible for the MODIS Fire Product and the MODIS Rapid Response System. He is a member of the NASA NPOESS Preparatory Project (NPP) Science Team. He is co-chair of the GOFC/GOLD-Fire Implementation Team, a project of the Global Terrestrial Observing System (GTOS), and a member of the Integrated Global Observation of Land (IGOL) Steering Committee. He is on the Strategic Objective Team for USAID's Central Africa Regional Project for the Environment. His current research is on land cover and land use change, the extent and impacts of global fire, global agricultural monitoring (with the U.S. Department of Agriculture Foreign Agricultural Service), and their associated information technology and decision support systems.

JOHN W. LEIBACHER is the director of the NSF-sponsored Global Oscillation Network Group (GONG) program and an astronomer at the National Solar Observatory. He is outgoing chair of the Solar Physics Division of the American Astronomical Society (AAS) and a member of the AAS Committee on Astronomy and Public Policy. Dr. Leibacher is involved in all aspects of helioseismology. Dr. Leibacher's NRC service includes membership on the Committee on Solar and Space Physics (chair, 1987-1990) and the Space Studies Board. His most recent NRC service was as a member of the Committee on PI-led Missions in the Space Sciences: Lessons Learned.

ROBERT P. LIN is a professor of physics and director of the Space Science Laboratory at the University of California, Berkeley. His research interests include solar and interplanetary physics, lunar and planetary studies, high-energy astrophysics, and the physics of Earth's magnetosphere. He is leading a program of high-resolution gamma-ray and hard x-ray spectroscopy of cosmic and solar sources. Dr. Lin is a fellow of the American Geophysical Union and is the recipient of the Docteur Honoris Causa de l'Universite de Toulouse, the NASA Mars Global Surveyor Group Achievement Award, and the NASA Lunar Prospector Group Achievement Award. He is the recipient of the NASA Ames Research Center Honor Award to Lunar Prospector Science Team and the NASA Goddard Space Flight Center Group Achievement Award for the HESSI Imaging Hardware Team. Dr. Lin served on the NRC Committee on Solar and Space Physics, and on the Panel on Solar and Space Physics of the Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion: A Vision for Beyond 2015.

MOLLY K. MACAULEY is a senior fellow with Resources for the Future in Washington, D.C. Her research interests include space economics and policy and the use of economic incentives in environmental regulation. Her other research projects include exploring the use of economic incentives to manage space debris; issues in space risks; the value of geostationary orbit; and the value of information, particularly information derived from space-based remote sensing. She is a member of the International Academy of Astronautics, the NRC Aeronautics and Space Engineering Board, and the Steering Committee for Workshops on Issues of Technology Development for Human and Robotic Exploration and Development of Space.

STEVEN R. MAJEWSKI is an associate professor in the Department of Astronomy at the University of Virginia. His research interests cover galactic structure, stellar populations, galaxy evolution, deep-space surveys, astrometry, infrared astronomy, and instrumentation. He is a science team member and key project principal investigator for the NASA Space Interferometry Mission. Since his graduate work at the University of Chicago's Yerkes Observatory, from which he received his Ph.D. in 1991, his research has concentrated on the evolution of galaxies and stellar populations, both from the perspective of studying extragalactic systems to high redshifts and through detailed study of the spatial, kinematical, and abundance distributions of populations in the Milky Way and its satellite system. In 1997 Dr. Majewski was awarded a David and Lucile Packard Foundation Fellowship, a National Science Foundation Career Award, and a Cottrell Scholar Award from the Research Corporation.

BARRY H. MAUK is a physicist and section supervisor in the Applied Physics Laboratory at Johns Hopkins University. Dr. Mauk's professional service includes co-investigator with NASA's Voyager Low Energy Charged Particles Investigation and NASA's Cassini Magnetospheric Imaging Instrument Investigation, team member of the Galileo Energetic Particle Detector investigation, instrument scientist on the Messenger Energetic Particle and Plasma Spectrometer investigation, mission scientist for the Living with a Star Geospace program, lead energetic particle investigator for the Magnetospheric Multiscale mission, and lead energetic particle investigator for the Juno New Frontiers mission. Dr. Mauk has served on the NRC Committee on Planetary and Lunar Exploration, NASA's Science Working Group Panel for the Inner Magnetospheric Imager, NASA's Multiprobes Mission Science Definition Team, and NASA's Sun-Earth Connections Roadmap Committee in 1999. He served as a member of NASA's Sun-Earth Connections Roadmap Committee in 2002. Dr. Mauk is a member of the NRC Committee on Distributed Arrays of Small Instruments for Research and Monitoring in Solar-Terrestrial Physics: A Workshop and of the Committee on Solar and Space Physics.

LOUISE M. PROCKTER is a planetary scientist at the Applied Physics Laboratory at Johns Hopkins University. Her research interests include surface process and morphology of icy satellites and asteroids. She has extensive involvement in the planning of the Galileo Europa mission, working with the imaging team and Galileo engineers at the Jet Propulsion Laboratory. She also participated in the Near Earth Asteroid Rendezvous (NEAR) mission and is currently the deputy instrument scientist for the MESSENGER mission. In 2003 she served as a member of the science definition team for the proposed Jupiter Icy Moons Orbiter and chaired the team's geology subgroup. Dr. Prockter is a member of the NRC Committee on Planetary and Lunar Exploration.

J. CRAIG WHEELER is the Samuel T. and Fern Yanagisawa Regents Professor of Astronomy at the University of Texas at Austin and past chair of the department. He is president-elect of the American Astronomical Society. His research interests cover supernovas, black holes, and astrobiology. He has published more than 200 scientific papers, an astronomy text, and a novel and has edited five books. A popular science lecturer, Dr. Wheeler has received many awards for his teaching. He was a visiting fellow at JILA and at the Japan Society for the Promotion of Science and was a Fulbright Fellow in Italy. He currently serves as co-chair of the NRC Committee on the Origins and Evolution of Life and is a member of the Space Studies Board. Dr. Wheeler previously served on the NRC Steering Committee for the Task Group on Space Astronomy and Astrophysics.

Staff

SANDRA J. GRAHAM, study director, received her Ph.D. in inorganic chemistry from Duke University in 1990. Her past research focused primarily on topics in bioinorganic chemistry, such as the exchange mechanisms and reaction chemistry of biological metal complexes and their analogs. From 1990 to 1994 she held the position of senior scientist at the Bionetics Corporation, where she worked in the science branch of the Microgravity Science and Applications Division at NASA headquarters. Since 1994 Dr. Graham has been a senior program officer at the Space Studies Board, where she has directed numerous studies, many with a focus on space life sciences and microgravity sciences.

DWAYNE A. DAY joined the Space Studies Board in 2005 as a research associate. Dr. Day received his Ph.D. in political science from George Washington University and has previously worked for the Columbia Accident Investigation Board and the Congressional Budget Office.

MATTHEW BROUGHTON, Space Studies Board summer undergraduate intern, is a senior at Augsburg College in Minnesota. He is currently pursuing a bachelor of science in physics and a bachelor of arts in

English. His undergraduate research has been in space physics, specifically the distribution of Pc 3-4 waves in the outer magnetosphere.

CATHERINE A. GRUBER is an assistant editor with the Space Studies Board (SSB). She joined the SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and has also worked as an outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.

CELESTE NAYLOR joined the NRC and the Space Studies Board in June 2002 as a senior project assistant. She has worked with the Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope and also with the Committee on Microgravity Research and the Task Group on Research on the International Space Station. Ms. Naylor is a member of the Society of Government Meeting Professionals and has more than 7 years of experience in event management.

D
Missions in NASA Strategic Roadmaps

TABLE D.1 Actual, Proposed, or Notional Missions Contained in NASA Strategic Roadmaps

Name or Notional Mission	Acronym	Roadmap(s)	Launch
Mars Global Surveyor	MGS	Mars	1996
Mars Odyssey		Mars	2001
Mars Express (ESA Mission)		Mars	2003
Mars Exploration Rovers (Spirit, Opportunity)	MER	Mars	2003
Mars Reconnaissance Orbiter	MRO	Mars	2005
Phoenix Lander/Mars Scout		Mars	2007
Mars Science Laboratory	MSL	Mars	2011
Mars Environment Mission	MEM	Mars	2013
Mars Sample Return	MSR	Mars	2016
Europa Geophysical Observer	EGO	Solar System	2010
Venus Surface Explorer		Solar System	2019
Titan Explorer		Solar System	2016
Juno (Jupiter Probe)		Solar System	2010
Europa Astrobiology		Solar System	2025
Neptune System		Solar System	2025
Gamma Ray Large Area Telescope	GLAST	Universe	2007
Herschel		Universe, Search for Earth-like Planets	2007
Planck		Universe	2007
Nuclear Spectroscopic Telescope Array	NuSTARR	Universe	2009
Widefield Infrared Survey Explorer	WISE	Universe, Search for Earth-like Planets	2009
James Webb Space Telescope	JWST	Universe, Search for Earth-like Planets	2011
Laser Interferometer Space Antenna	LISA	Universe	2015
Constellation-X	Con-X	Universe	~2017
Joint Dark Energy Mission	JDEM	Universe	~2016
Black Hole Finder Probe	BHFP	Universe	~2020

TABLE D.1 continued

Name or Notional Mission	Acronym	Roadmap(s)	Launch
Inflation Probe	IP	Universe	~2024
Big Bang Observer	BBO	Universe	~2025
Black Hole Imager	BHI	Universe	~2025
Pathways to Life Observatories		Universe	~2025
Large Ultraviolet/Optical Telescope	LUVO	Universe, Search for Earth-like Planets	2025-2035
Ultraviolet/Optical Interferometer	UVOI	Universe	2025-2035
Far Infrared/Submillimeter Interferometer	FIRSI	Universe, Search for Earth-like Planets	2025-2035
Early Universe X-ray Observer	EUXO	Universe	2025-2035
Nuclear Astrophysics Compton Telescope	NACT	Universe	2025-2035
Large Binocular Telescope Interferometer	LBTI	Search for Earth-like Planets	2005-2015
Stratospheric Observatory for Infrared Astronomy	SOFIA	Search for Earth-like Planets, Universe	2006
Kepler		Search for Earth-like Planets	2008
Space Interferometry Mission–PlanetQuest	SIM–PlanetQuest	Search for Earth-like Planets	2011
Terrestrial Planet Finder-Coronograph	TPF-C	Search for Earth-like Planets	2014
Terrestrial Planet Finder-Interferometer	TPF-I	Search for Earth-like Planets	2015-2025
Single Aperture Far-Infrared	SAFIR	Search for Earth-like Planets, Universe	2015-2025
Life Finder		Search for Earth-like Planets	2025-2035
Planet Imager		Search for Earth-like Planets	2025-2035
Multi-angle spectropolarimetric imaging; 3-D aerosol profiling (LEO)		Earth Science	2005-2015
UV/Vis/NIR Imaging (Sentinel Orbit, L1, or GEO)		Earth Science	2005-2015
Cal/Val free-flyer (LEO)		Earth Science	2005-2015
High-resolution ice altimetry (LEO)		Earth Science	2005-2015
3-D ocean altimetry (LEO)		Earth Science	2005-2015
Hyperspectral imaging instrument for solar UV, EUV, and X-rays (L1)		Earth Science	2005-2015
Synthetic Aperture Radar and/or passive microwave		Earth Science	2005-2015
Combined 3-D structure and multispectral imaging (LEO)		Earth Science	2005-2015
3-D laser profiling (LEO)		Earth Science	2005-2015
Precision geodetic imaging (LEO)		Earth Science	2005-2015

TABLE D.1 continued

Name or Notional Mission	Acronym	Roadmap(s)	Launch
Wide-swath microwave 3-D sounding (MEO)		Earth Science	2015-2025
Continuous, spectrally resolved solar occultation (L2)		Earth Science	2015-2025
High-resolution ice altimetry (LEO)		Earth Science	2015-2025
Ice penetrating radar (LEO)		Earth Science	2015-2025
Combined ocean surface/lower atmosphere winds (LEO)		Earth Science	2015-2025
3-D clouds—Cloudsat-Calipso follow-on (LEO)		Earth Science	2015-2025
Cal/Val instruments for NPOESS follow-on (LEO)		Earth Science	2015-2025
Wide-swath 3-D cloud and aerosol profiling (LEO)		Earth Science	2015-2025
Precision/interferometric altimetry (LEO)		Earth Science	2015-2025
Microwave radar/radiometry—Aquarius/Hydros follow-on (LEO)		Earth Science	2015-2025
Time-variable gravity—GRACE follow-on (LEO)		Earth Science	2015-2025
3-D profiling—Cloudsat-Calipso follow-on (LEO)		Earth Science	2015-2025
3-D rain profiling (LEO)		Earth Science	2015-2025
Hyperspectral imaging (LEO)		Earth Science	2015-2025
Ground-penetrating active microwave (LEO)		Earth Science	2015-2025
High-performance ocean color imaging (UV/Vis/NIR) (LEO or GEO), supporting sea-surface temperature and salinity measurements		Earth Science	2015-2025
Upper-ocean profiling (e.g., via blue/green lidar) (LEO)		Earth Science	2015-2025
Hyperspectral imager (GEO or L1)		Earth Science	2015-2025
High performance hyperspectral UV/Vis/NIR imaging (LEO or GEO)		Earth Science	2015-2025
Combined 3-D structure and multispectral imaging (e.g., radar, lidar, and multispectral visible imaging) (LEO)		Earth Science	2015-2025
Frequent, precision geodetic imaging (MEO constellation)		Earth Science	2015-2025
Distributed magnetometry (e.g., 12-satellite constellation, LEO, 300-800 km, low-inclination and polar orbits)		Earth Science	2015-2025
Passive/active microwave (MEO)		Earth Science	2025-2035
Active/passive microwave (3 GEO)		Earth Science	2025-2035
Cal/Val instruments for NPOESS follow-on		Earth Science	2025-2035

TABLE D.1 continued

Name or Notional Mission	Acronym	Roadmap(s)	Launch
High-performance ocean color imager (UV/Vis/NIR) (GEO); supporting sea-surface temperature and salinity measurements		Earth Science	2025-2035
Hyperspectral UV/Vis/NIR imaging (LEO)		Earth Science	2025-2035
Combined 3-D structure and multispectral imaging (e.g., lidar and multispectral Vis imaging) (LEO)		Earth Science	2025-2035
High-temporal-resolution geodetic imaging (GEO)		Earth Science	2025-2035
Multispectral imaging in thermal IR (LEO)		Earth Science	2025-2035
3-D land structure (e.g., lidar and/or InSAR) (LEO)		Earth Science	2025-2035
Glory		Earth Science	2005-2010
Orbiting Carbon Observatory	OCO	Earth Science	2007
Ocean Surface Topography Mission	OSTM	Earth Science	2005-2010
NPOESS Preparatory Project	NPP	Earth Science	2006
CloudSat		Earth Science	2005
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations	CALIPSO	Earth Science	2005
Global Precipitation Measurement	GPM	Earth Science	2010
Hydrosphere State Mission	Hydros	Earth Science	2010
Aquarius		Earth Science	2008
Landsat Data Continuity Mission	LDCM	Earth Science	2009
Aeronomy of Ice in the Mesosphere	AIM	Sun-Solar System	2005-2015
Geospace Electrodynamic Connections	GEC	Sun-Solar System	2017
Farside Sentinel	FS	Sun-Solar System	2025-2035
Heliostorm		Sun-Solar System	2016-2020
Inner Heliospheric Sentinels	IHS	Sun-Solar System	~2013
Ionosphere-Thermosphere Storm Probes	ITSP	Sun-Solar System	2015
L1 Earth-Sun		Sun-Solar System	2015-2020
L1 Mission		Sun-Solar System	TBD
Magnetospheric Multi-Scale	MMS	Sun-Solar System	2011
Radiation Belt Storm Probes	RBSP	Sun-Solar System	2011
Solar-B		Sun-Solar System	2006
Solar Dynamics Observatory	SDO	Sun-Solar System	2008
Solar Sail Demo		Sun-Solar System	2010-2014
Solar Orbiter		Sun-Solar System	2015-2025
Solar Probe		Sun-Solar System	2005-2015

TABLE D.1 continued

Name or Notional Mission	Acronym	Roadmap(s)	Launch
Solar-Terrestrial Relations Observatory	STEREO	Sun-Solar System	2006
Time History of Events and Macroscale Interactions During Substorms	THEMIS	Sun-Solar System	2006
Aeronomy and Dynamics at Mars	ADAM	Sun-Solar System	2015-2020
Auroral Acceleration Multiprobe	AAMP	Sun-Solar System	2015-2025
Dayside Boundary Constellation	DBC	Sun-Solar System	2025-2035
Doppler		Sun-Solar System	2015-2020
Geospace Magnetospheric and Ionospheric Neutral Imager	GEMINI	Sun-Solar System	2015-2025
Inner Magnetospheric Constellation	IMC	Sun-Solar System	2025-2035
Ionosphere Thermosphere Mesosphere Waves	ITM-Waves	Sun-Solar System	2020-2025
Interstellar Probe	IP	Sun-Solar System	2025-2035
Io Electrodynamics	IE	Sun-Solar System	2015-2035
Jupiter Polar Orbiter	JPO	Sun-Solar System	2015-2035
Magnetospheric Constellation (MagCon)	MC	Sun-Solar System	2015-2025
Magnetosphere-Ionosphere Observatory	MIO	Sun-Solar System	>2035
Mars Atmospheric Reconnaissance Survey	MARS	Sun-Solar System	2025-2035
Magnetic Transition Region Probe	MTRAP	Sun-Solar System	2025-2035
Reconnection and Microscale	RAM	Sun-Solar System	2020-2035
Solar Heliospheric and Interplanetary Environment Lookout in Deep Space	SHIELDS	Sun-Solar System	2025-2035
Solar Connection Observatory for Planetary Environments	SCOPE	Sun-Solar System	>2035
Solar Energetic Particle Mission	SEPM	Sun-Solar System	2015-2035
Solar Polar Imager	SPI	Sun-Solar System	2020-2035
Solar Weather Buoys	SWBs	Sun-Solar System	2022
Sun-Earth Coupling by Energetic Particles	SECP	Sun-Solar System	2020-2025
Stellar Imager	SI	Sun-Solar System	2025-2030
Tropical ITM Coupler	T-ITMC	Sun-Solar System	2020-2035
Venus Aeronomy Probe	VAP	Sun-Solar System	2025-2035